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Spatial analysis of hydrogen production from renewable energy sources for injection in natural gas grid. Canada case study

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Summary

1. Introduction

The objective of the study has been to find areas of Canada suitable for with renewable energy sources (RES) suitable for the production of hydrogen to be injected in the natural gas grid. In the following study different themes concerning the current energy transition has merged together in the specific contest of Canada. The country is facing the climate issues with a series of politics and actions to decarbonize its energy system, strongly bounded to the fossil fuel industry. In the contest of its specific characteristics it is developed an analysis on the availability of renewable sources for hydrogen production. The molecule is getting growing importance for the potential to unlock the decarbonization of specifics but consistent fractions of the final energy consumption. At the same the development of a hydrogen production industry is linked to too many uncertainties, including the way to develop a proper infrastructure to link production and consumption. One of the solution nowadays explored is the use of the existing natural gas pipelines, limited by the mainly by the structural characteristic of the natural gas system. Studies, policies, experiences and projects are moving in this direction, and the possibilities for a Canadian application are explored in the study. The method used derive from different studies that make use of Geographic Information System software and data both to quantify and localise the renewable energy sources potentials. Starting from this references and using appropriate data and elaborations, a procedure has been establish to identify the areas of interest for renewable energy production of hydrogen on purpose of hydrogen, with the end to mix it with natural gas in transportation pipelines. To perform the analysis it has been used the GIS software ArcMap 10.6, within the ArcGis Desktop suite, released under license at Politecnico di Torino students.

1.1 Hydrogen

Hydrogen is getting growing attention for its potentials in the transition towards a lower carbon intensive energy system. International sectorial organizations expect that hydrogen will cover a share of the total final energy consumption by 2050 that goes from 6% (IRENA, International Renewable Energy Agency) up to 18% (Hydrogen Council) [1]. Many countries announced and developed politics to support hydrogen technologies in different sectors [2], along with an increasing number of companies that direct investments in this field. That is not the first time hydrogen is at centre of interest, but changing conditions in the energy system and a shift in its use paradigm make this occasion a more solid one. To understand the reasons of this difference it is necessary to look at role that hydrogen can play in the energy transition.

Hydrogen in its molecular gaseous form H_2 can be categorize as an energy vector, not an energy source. This molecule is rare on Earth and not available in nature in a reservoir from which it can be extracted. It is produced starting from more complex molecules where H atoms are linked in bonds with others elements. Production of hydrogen is already a common practice in the industrial sector: the output of the industry in 2018 amounted at around 115 Mt/yr, 70 Mt of pure and 45 Mt of hydrogen mixed with other gases [3]. That is roughly equal to the 3.3% of the 2018 final energy consumption [4] (using for the estimation a LHV = 119.73 MJ/kg). The production is largely based on the extraction of the molecule via chemical processes from fossil fuels, that have molecular structures mostly based on carbon and hydrogen. These routes covers 96% of total production, shared among natural gas (48%), oil (30%) and coal (18%) [5]. The remaining production (4%) is almost totally obtained by electrolysis, a technology that uses electricity to decompose molecules exploiting electrochemical principles [6]. Hydrogen that results from this path is mostly a by-product of other productions, like in the case of chlor-alkali electrolysis to manufacture chlorine that guarantee 2% of overall consumption [2]. What is considered the most interesting technology for future large scale production, water electrolysis or hydrolysis, represents nowadays only a tiny fraction of overall consumption. It is mostly deployed in chemical industries, where a high purity hydrogen stream is required, and only in few cases for massive production. The electricity used for electrolysis is usually provided by the electric grid, so it is not in principle a zero carbon emission route. Considering the overall hydrogen production, only 0.7% of it comes from renewable energy sources (RES) or plants coupled with carbon capture, utilization and storage (CCUS) technologies. The remaining share causes every year the production of around 830 Mt of CO_2 and the direct emission of at least 700 Mt [2], more than 2% of 2018 energy related CO_2 emissions [7] and around 1.35% of total global CO_2 equivalent GHG emissions [8].

This production satisfy an existing demand that mostly comes from industrial applications. Hydrogen is used for oil refining (33% of total consumption), as a feedstock in ammonia (27%) and methanol (11%) production, in iron and steel production (3%) and other industrial processes, like production of heat from mixed hydrogen that results as industrial gaseous by-product. The consumption of hydrogen in these sectors continued to grow in the past years and will maintain the trend in coming ones, mostly driven by refined oil products and ammonia based fertilizer demands [2].

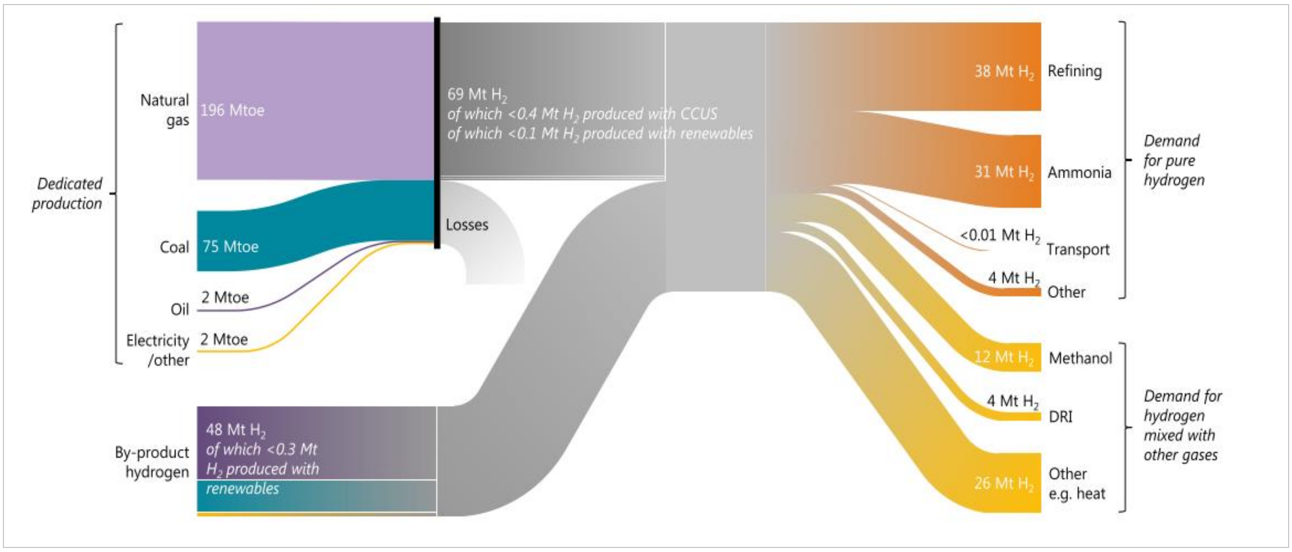


Figure 1 Current hydrogen production and consumption pathways [2]

The consume in most advanced applications, that are generally considered as the most interesting one for the future energy system, represents only a tiny fraction of today total. The most efficient way to exploit the molecule as an energy carrier is to use it in a fuel cell (FC), the device that produces electricity through electrochemical processes, using the chemical potential of redox reactions between specific molecules . Usually pure hydrogen is used in combination with oxygen (pure or atmospherically one in air) to produce electricity and water is the only by-product of this reaction.

The FCs can be used in heavy and light duty vehicles, properly fuel cell electric vehicles (FCEVs), as well for railroad and maritime transportation, and they feed the electric motor in substitutions of close batteries. They are used for cogeneration of heat and power in industrial and residential buildings, in back-up systems and in power-to-power installations for grid storage via hydrogen. These kind of applications were at the centre of 2000s interest for hydrogen deployment, but the high cost of the fuel cells and pure hydrogen production, the difficulties to establish a hydrogen supply chain and, in recent years, the relatively cheaper solution of batteries electric vehicles (BEVs) to decarbonize light mobility prevented any development in the direction of market scale.

1.1.2 Role of hydrogen in future energy system

The applications that many agencies, organizations, companies and government departments foresee for hydrogen are based on a different paradigm than the one already analysed. The idea on which role hydrogen can play in future varies from case to case [1, 2, 8–14], but the basic idea is the same: it will represent a mean to increase the share of low and zero carbon energy sources in total final energy consumption. Hydrogen would represent the way to unify the decrease of carbon emissions and the use of a stable energy carrier with a high energy density, a role today played by the fossil fuels. In fact it is at the same time a molecule, so a chemical compound, but can be largely produced from zero carbon sources. Similar alternatives in the contest of energy transition are offered by biomass sources, that can be used for the production of solid, liquid and gaseous fuels. Their use is not emission free, but because of their life cycle and their fast reproduction, they are considered both zero carbon and renewable energy sources. At the same time biomass energy sources have many issues, for example related to their extensive production. Hydrogen could offer an alternative that is at same time largely available, renewable, emission free and with characteristic similar, for some aspects, to a fossil fuel. Like power system, its role can be analyse in the three sections of energy production, transportation and consumption.

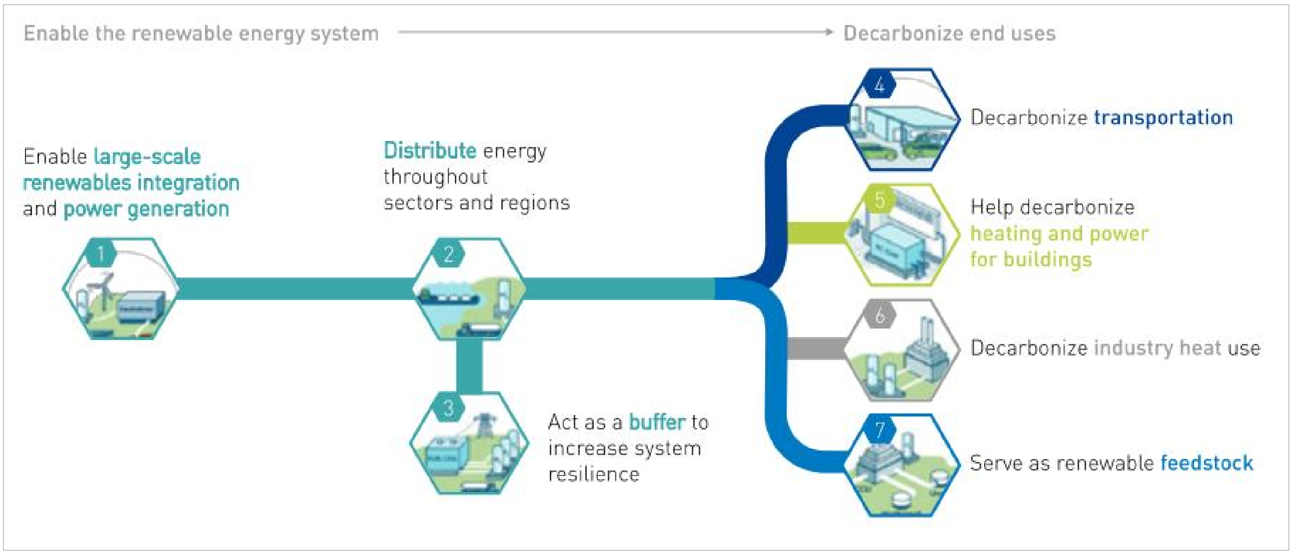


Figure 2 Hydrogen energy system [14]

The image give a visual representation of the potential future role of hydrogen, in particular highlighting the sense of energy connection. Following the same logic, it is explained the potential of hydrogen in the energy system. Starting from the consumption, hydrogen can be deployed in different sectors. The first one is the industry, where hydrogen is almost totally used today. Industries that use hydrogen in their production processes will continue to consume the same molecule, but from a different source. Many strategies for the hydrogen development consider this transition as the early stage of the more advanced one, the place where to develop the practices and rise the demand, thus diminish the prices, for the zero emission hydrogen [15]. The other application in the sector is heat, today produced with fossil fuels combustion. Industrial heat can be at different levels of temperature, and if low temperature heat can be replaced by electrification, for high temperature one hydrogen seem to be the best solution [3]. Two important examples are the steel and concrete industries, responsible of large emissions.

Heat and power can be produced from hydrogen to cover commercial and residential buildings loads. The production of power with stationary application of FC (and heat, in the case of solid oxide fuel cells) for small or centralized loads is one of the possible solutions. In countries like Japan, Korea and in California there are some applications in this sense, but they are currently a minority. The last development in this direction are mostly related to the replacement of diesel back-up systems (like in the Microsoft data centre experimental case) or diesel generators in areas not connected to the power grid. In long term the idea is to use FC application, centralized or on territory, to replace power generation from natural gas [9]. The production of heat can occur not only via the electrochemical transformation, but also with combustion. It is a less efficient way, but also more cheaper one and compatible with the existing devices. The boilers largely used for space heating using natural gas can use a mixture with up to the 5%-10% of hydrogen without major issues, according to different estimation [16,17]. They are also already available in the market furnaces that are able to safely work with a hydrogen-natural gas mixture as well burning pure hydrogen. That option is also related to the potential transformation of the entire natural gas system, the central theme of the study that will be largely developed in following chapters. The last proper consumption demand can come from the transportation. As already explained the development for light vehicles is nowadays brake by the larger convenience of the BEVs. That occurs not only for their cost, that continues to decline, but also to the availability of a potential loading infrastructure that is the power grid. Hydrogen, with the exception of some advanced areas of the world, does not have such an infrastructure. In short term there is a major interest related to heavy duty road transportation, like for trucks, or public transportation, like buses, for which hydrogen could offer a better option to increase autonomy range. For marine and aviation transportation, hydrogen could be the only solution for large scale decarbonization. It can be use both to feed FC and to produce synthetic fuels for internal combustion engines. All of the applications summarized above are or in an experimental phase or represent marginal solutions within their reference market. Reports often forecast the volumes of a future hydrogen economy as a consequence of demand replacement in different sectors [13], but this substitution, in the early stages, cannot occurs but with the implementation of clear politics in this direction.

The last application is the one reported in the infographic (figure 2) as “buffer to increase the system resilience”. It is neither a final use consumption nor a proper consume at all, but can be consider a virtual one. Represents the possibility to use hydrogen as storage to balance the power grid [18].

There could be different solutions, but the basic idea is the same: produce hydrogen via electrolysis when there is a grid overplus, store it and produce power using it when there is a higher demand. The differences are related to the used technologies for both conversion paths, to the size of installation, to its location (eg along the power line or directly attached to a wind farm), to the way hydrogen is stored (locally accumulated or delivered to a hydrogen infrastructure). It is one of the possible alternatives for the management of power grid, particularly important for the unbalances that the RES production discontinuity can determine on the power grid. The system integrates both the consumption and the production element of the hydrogen supply chain.

1.1.3 Green hydrogen

In the previous chapters it has been referred to the hydrogen production of the future energy system not only as a zero-carbon one, but also renewable. There is a clear difference between the two categories, and it is embodied by the so called *blue hydrogen*. Under this name fall the hydrogen produced with the processes that extract the molecule from fossil fuels, but coupled with carbon capture utilization and storages (CCUS) technologies. The emissions are reduced by 85%-95% and at the same time the production rely on the same resources, so mostly on natural gas. The alternative is the production from renewable sources, that possibly comprehends the use of any typology of renewable energy source [5]. Among them, only two routes can be considered ready for the large scale production of hydrogen: steam reforming of biomass or biogas and water electrolysis using power produced by renewable energy sources. With the term of *green hydrogen* it is generally indicated the second category, also if it is often used as if comprehensive of all the renewable alternatives. Most precisely it is referred to the cases that use a mature renewable energy source as power source, and the reason is mostly explained by the picture below (figure 3).

The levelized cost of hydrogen (LCOH) is estimated by IRENA for different prices of RES and of electrolysers cost. The best cases for green hydrogen (yellow = solar PV; blue = wind) are achieved with lower electricity and electrolyser costs. The best case of wind is in reality an extreme estimation, based on the most optimistic data for both of them around the world. In reality different forecasts delay to the 2040/2050 the possibility for green hydrogen to reach a competitive level with blue hydrogen. Production from fossil fuels without CC(U)S is even cheaper, without and adequate carbon price. The graph is quite simple and it is mostly a summary of the worldwide situation. A more detailed one would have distinguish among different areas. In fact is technology can be slightly affected, the location have a strong impact on the fuel cost. A clear example is the case of current production of hydrogen in China: it largely rely from the cheap coal resources, and the 80% of the technology capacity is installed here. In the same way a competitive green hydrogen production require both the reduction of electrolyser costs and an abundant production of renewable energy.

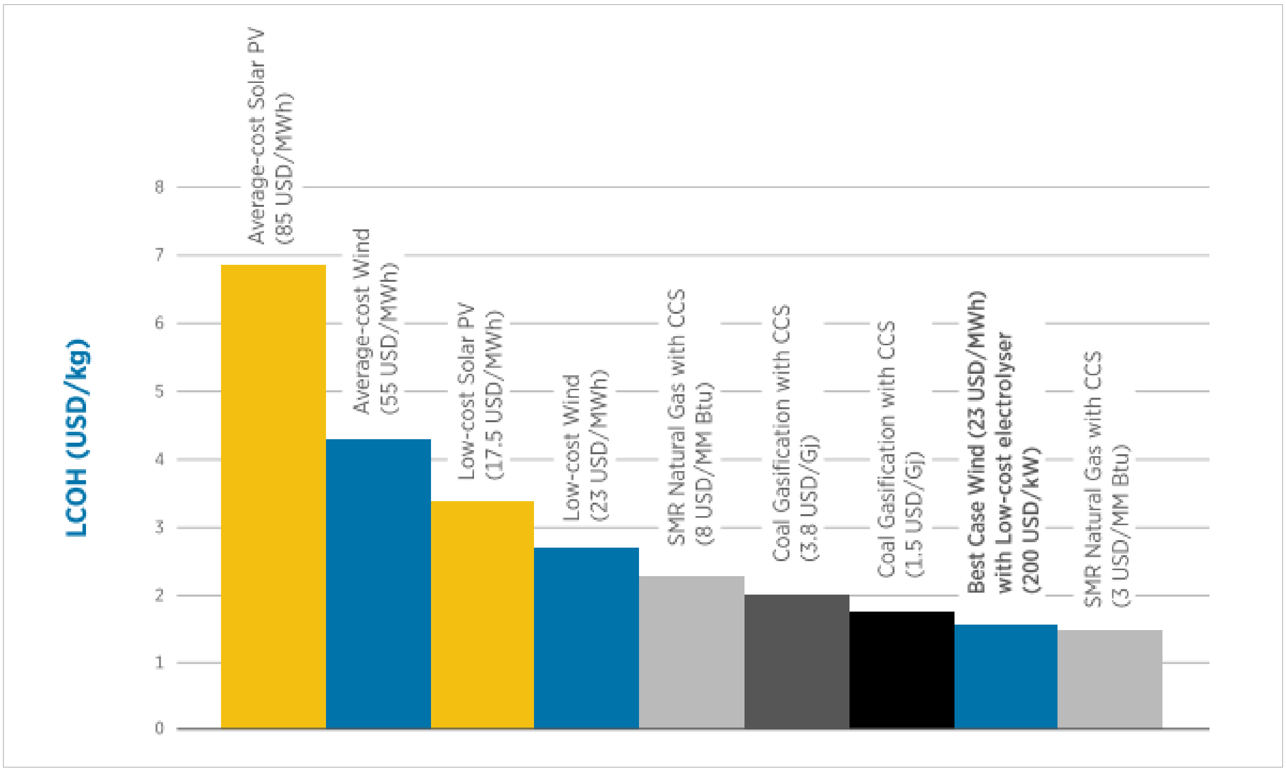


Figure 3 Hydrogen production costs for different technology options, 2018 [1]

The electrolyser technology has been around for around one century, in the form of Alkaline electrolysers. More advanced concepts are the Proton Exchange Membrane (PEM) electrolysers, commercial from around 15 years, or the Anion Exchange Membrane (AEM), similar to the previous one but with different working principle and lower market penetration [19]. The Solid Oxid Electrolysis (SOE) is a proven technology, but with up to now at the level of experimental applications. Other technologies could be available, but not ready for the scale of the integration in the sector. The scale of the possible electrolysers installation is one of the main elements that breaks its possible development. While Alkaline cells can already reach the scale of hundreds of MW, and has been already used for industrial scale pure hydrogen production in areas with abundant RES production, PEM and AEM still remain below the 10 MW levels [6]. The problem is not related to the dimensions themselves, cause the electrolysers can be easily scaled up with dimensions or used in series. The cost of the cell itself is not largely affected by the increase of scale production, but the unavailability of a large productive system determine the rise of costs. Electrolysers are today produced for small markets, and that determine a certain supply chain structure of the industry that rises costs. Innovation can play a role in reduction of the structural cost of the machines, but it is mostly the enlargement of the industry itself and thus the optimization of manufacturing processes that will represent the key step to a larger deployment. That is the reason of the politics that point to a fossil to green hydrogen (or at least electricity hydrogen) production: to create an early demand for the industry to speed up its development [15].

The other aspect is the one related to the electricity production from RES, and particularly from mature one in the sense of those technologies that are already competitive with power production from fossil fuels (natural gas and coal). Among them there are hydropower, that is already established as an affordable power source, solar photovoltaics (PV) and wind turbines, that are quickly expanding their areas of profitability around the world. Other solutions, like concentration solar power (CSP), can play locally an important role. The direct use of renewable sources to supply electrolysis is currently feasible from the technical point of view. The electrolysers technologies, and especially PEM, are able to work with different power input dynamics [20], and are scalable so can be apply in a variety of renewable power generation contests. The only limit for the application is again related to the cost of production: despite being a source that can rely on "free fuel", renewables has to pay back their cost and at the same time to be profitable for the companies. That make hydrogen production in direct competition with power production to be sold to the grid, so renewable cannot be assumed as a cost free source. The International Energy Agency (IEA) estimated the worldwide cost for production from solar PV and wind systems, and the following map resulted from the study (figure 4).

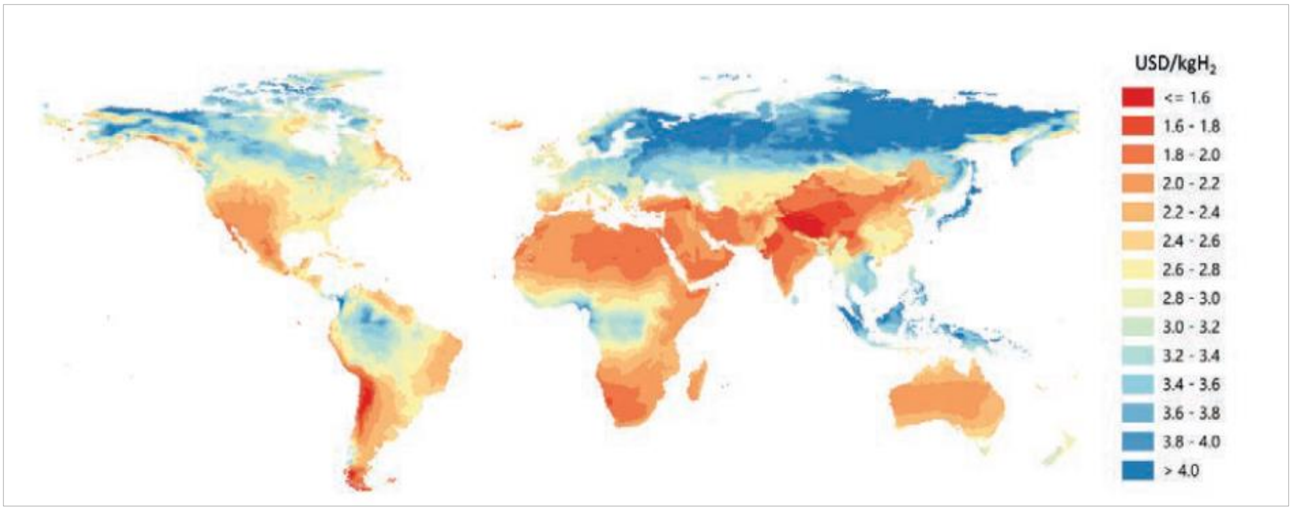


Figure 4 Hydrogen costs from hybrid solar PV and onshore wind systems in the long term [2]

The value obtained consider a combination of the two sources, but what it is important to highlight is again the high dependency of the location: assuming the access to the same electrolysis technology, the cost varies with the location as a consequences of the different radiation and solar conditions, that are the source for power generation. Considering what observed in figure 3, the upper and lower thresholds are around 2.5 and 1.5 USD/kg$_{H2}$, thus only few areas of world (dark orange to red) can offer hydrogen resources profitable for energy production. The option of the use of power from the grid for dedicated hydrogen production is currently not compatible with zero emission and renewable standards; in future it will more probably play the ancillary role of grid stabilizer already analysed than of dedicated commodity production. There is also a tecno-economic limit to that, and is related to the capacity factor of the electrolysers: the more they are high, the more the hydrogen cost will be lower. So a dedicated production will always be more profitable than a production from limited curtailments of renewable overproduction, if compared from the point of hydrogen cost (so not accounting for possible revenues for power sold to the grid).

1.1.4 Hydrogen blending

Transportation of hydrogen produced from renewable is the element of the system that actively realize the purpose of the production. In fact the production of a chemical like hydrogen make available, at the cost of energy lost in the conversion process, a more stable and storable form of energy than electricity. That can potentially open the way not only to a larger share of the RES in to the hard to penetrate sectors, but also to the development of the renewable market no more on a local, but on an international scale. This is not only a mystification, but companies and countries (like already quoted Japan and Korea, that cannot largely develop renewables on their relatively small territories) are already working in this direction. Despite being a key element in the future system, a hydrogen transportation infrastructure is far to come. With the lack of a larger and determined demand, the investments for a service to connect consumption and production are not justified. At the same time a variety of solutions have been already proven from a technical point of view, the differ in the used mean but also on the state of transported hydrogen.

While the production and consumption devices are based on the gaseous state of the molecule, transportation could rely also on liquid one. The gaseous form is the more direct one, that would require no state transformation. It can be stored in high pressure vessels (up to 700 bar) to obtain a good energy density despite the molecule low density (around 0.08376 kg/m^3 at ambient conditions T = 298.15 K and P = 1.01325 bar). The problem of low density and thus low energy density can be overcome by a change of state, transforming gas into liquid. It is necessary to use cryogenic liquefaction for the process, and the boiling point of hydrogen at ambient pressure is 21 K. The process is complicated by the molecular properties of hydrogen and the active cooling system needed to maintain the temperature require a quantity of energy roughly equal to the 25%-40% of the overall converted hydrogen. The result is a liquid hydrogen density of 71 kg/m^3, around 850 times more than gaseous one. The process is technically feasible and application are experimented for a large scale application. The main example is the first ship for marine transportation of liquid hydrogen realised by Kawasaki Heavy Industries. The other liquid options are related to the production of ammonia or liquid organic hydrogen carriers (LOHCs). In the first case there is a real production while in the second one the organic molecules absorb the hydrogen with a catalytic processes. Also in this cases a part of the energy is lost in the process. These forms of hydrogen can be transported on the road, shipped, loaded on trains or deployed by the use of a pipeline. Each mean can take advantages or disadvantages from an hydrogen form, and thus the application will determine which kind of hydrogen will be used.

The current study focus in particular on the possibility to develop a hydrogen infrastructure on land, for hydrogen transportation on long distances. In the existing applications, the gaseous fossil fuel are deployed by pipelines, trucks loaded with vessels and also liquid forms (eg LNG). The solution of pipeline can be applied to the case of hydrogen, and it is an application already in place. Around the world there are around 5000 km of pipelines for hydrogen transportation. They are mostly infrastructure that transfer the gas directly from the production plants to the consumption one, mostly chemical industries and refineries. The technology for its deployment is thus available, even if it can suffer at the beginning of the same scale limits already considered for the electrolysers.

Figure 5 Possible forms and means for hydrogen transportation at different levels of the supply chain, [2]

Studies on the possibility to develop a similar infrastructure on national scale, in order to optimize its temporal and spatial development, has been performed in a refined way for many for different territories [21-24]. Considering both the possibilities of local/national resources use (both green and blue hydrogen) and the availability of hydrogen imports, they design an optimal infrastructural solution to deploy hydrogen to potential consumption areas.

The limits that the practical realization encounters are the same of other transportation solutions, and even worst. In addition of the need and thus economic resources justification, a pipeline determine an important impact on the territory. Here the problem become somehow circular, because the quantitative limits of road deployment limit the interest and the availability for final demand, that thus never increase and production and infrastructure investments remain unjustified. Also with the intervention of governments, that are in any case necessary, the development of a completely new pipeline grid would require a certain time.

The injection of hydrogen in the existing natural gas (NG) pipelines represents a possible alternative to the construction of completely new infrastructure. It could represent the early stage of the total conversion of the NG network, that already connects gathering and consumption areas. This solution presents opportunities and difficulties [2,17,25,26], and this one in particular determine the impossibility of a complete conversion and the limit of a mixing with ng. Before to consider the structural limits imposed by the nature of the pipeline, it is necessary to consider a quantitative limit. To completely replace the volume of natural gas delivered with hydrogen they would be necessary $3900*10^9$ m^3 (2018) of hydrogen, while to deliver the same amount of energy it would be necessary 70% more of this value. This are quantities not available in short term (and maybe in long one too), and in fact all previsions consider possible the reconversion to the new use only a part of the existing pipeline. But the main limits derive from the deployment of hydrogen in an infrastructure designed for the transportation of a different gas [27,28]. First of all limits can be divided among the regulative and the technical one. While this second category reflect the possible impact of the mixture on the network, the first is the legal limit that can be reached according to national legislation. It is based not only on the need to guarantee the safety of the grid, but also to guarantee the quality of the gas delivered from the providers. This limits largely varies for different countries, and while in some cases measures to develop in hydrogen injection has been adopted (France, Austria, Germany with flexible limits), the majority of them maintain a value below 1%, with the exception of experimental activities. The main barrier in that case is not even the national limitation, but the fact that natural gas networks connect countries with a variety of normative in that sense, like in the case of Europe. The legislation was up to now developed for the specific use of the line, but the development of systemic gas injection would require a general upgrade or a unification of the norms. The technical limits are related to the different elements that compose the sections of the transportation system and the devices that use natural gas [16,28].

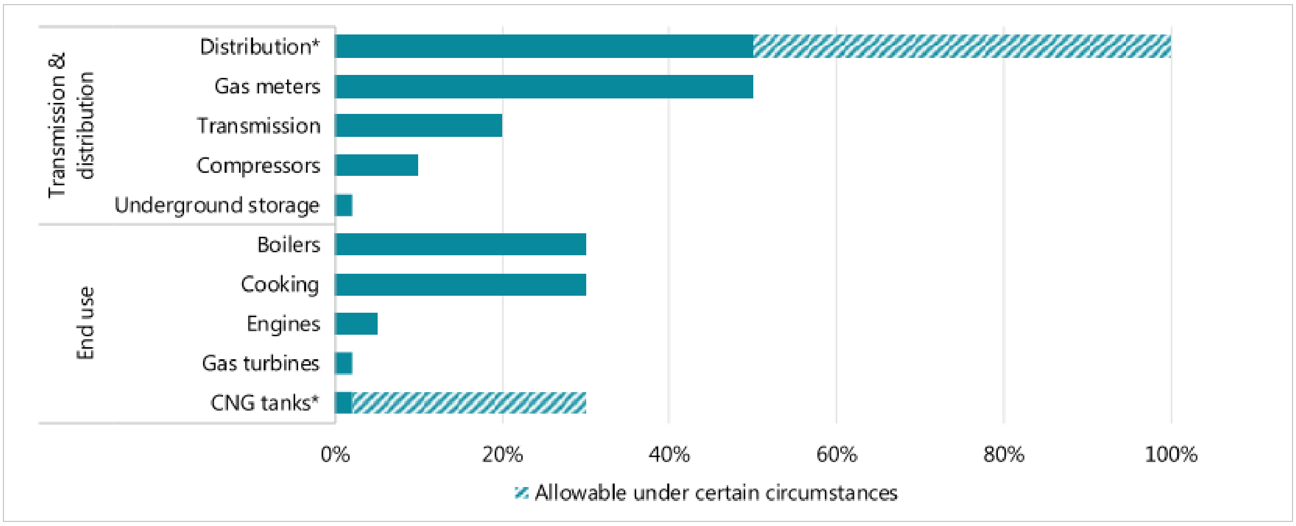


Figure 6 Technical current limits of gas blending in natural gas network [2]

For transmission and distribution pipelines there is a differentiation, with the first allowing in general lower values than the second one. That is mostly due to the material (carbon steel with protective coating [29]) that interacting with hydrogen molecule can induce embrittlement, thus a weakening and potential cracks in the pipes. Other issues are related to the safety and the suitability of the instrumentations that serves the infrastructure needs [30]. While some of them can be easily adapted or substituted, the system of turbo compressors that maintain the levels of can suffer the change of fuel characteristics. Tests on machine designed to operate on wider fuel conditions are already in place. Underground storage values can vary with the typology, with the salt cavern being the more suitable while the presence of aquifers can generate contaminates. Some of the final use devices can be adapted with new standards to optimize the fuel/air ratio and prevent the risk of flashback that can be caused by the hydrogen high flame speed [31]. Engines and turbines suffer more the presence of hydrogen for the specific of their designs, and can be less easily replaced. The general picture is that designs and materials can determine the rise of problems, but a low level of blending is admissible for almost every device. That can be the starting point for a progressive transformation and substitution. Once a level of hydrogen injection will be chosen, it has to be establish a system for the control of the mixture quality. In fact the injection in different points of the line would possibly determine the change of the percentage. If not managed, that can determine a discontinuity in the stream properties and affect the performances of the devices fed with the gas mixture. A last element to consider is the economic one: the production costs of green hydrogen is higher than natural gas for market value, and will remain like that for long time if the production remains in a small scale [32]. The consequence would be the increase of the cost to the consumer for the same volume of gas, thus lower amount of energy.

Despite all these problems, the clear advantage is that there is an infrastructure almost ready to use. All the costs related to a new pipeline can be avoided, or diluted in time with a progressive transition to an higher content of hydrogen. The result could be the development of an economy of renewable energy exchanges based on hydrogen. While power is the primary production of RES, its transportation is potentially problematic and require a short term management to guarantee the grid balance at each moment. That collide with the high variability of renewables, and to solve the problem the theme of energy storage has become central. Hydrogen injection in the grid can represent a way to deliver green hydrogen from areas with high RES potential to those with high energy consume. Once mixed with ng, hydrogen can be used in the final applications that already use gas, or be separated downstream to obtain back a pure hydrogen gas. That second option can be performed with a series of technologies, like pressure swing adsorption (PSA), membrane separation or electrochemical separation. They are all quite effective, with a recovery rate around the 80%. At the same their cost range between 0.2 US$/kg$_{H2}$ and 8 US$/kg$_{H2}$, depending on the position on the line where the extraction is performed and the utilization rate of the device [17]. Compared to the current objectives for competitive green hydrogen cost, that seem not an affordable option in short term. The other solution is that hydrogen remains in to the stream and is used by final consumers fed by the ng network, that basically mean it is burnt [33]. That results in a partial decarbonization of final use applications that use gas mostly for the production of heat. For example a mixture of 20% of hydrogen will release around -20% of carbon dioxide if emissions are calculated on volumetric base (g/m^3), less than -7% if on the base of delivered energy (g/MJ, calculate on the LHV). The second value is more significative; also if lowered by the lower LHV of hydrogen, mixing can produce an important reduction of carbon dioxide emissions. It is a feasible way to decarbonise the production of heat in different sectors, where it is difficult the penetration of renewable and zero emissions sources.

Studies, test experiences and projects are already in place across the world, and mostly in Europe [34-37]. The demonstrations already in place mostly produce hydrogen with electrolysis, but using power from the grid. Other experiences use vessels of gas manufactured from fossil fuels to test the behaviour of the pipes and final use devices, both at transmission and delivery level. The national or international scale projects [26,38,39] foresee the early deployment of blue hydrogen as first source of hydrogen for injection, progressively replaced by green hydrogen when this will be available in large quantities and lower prices. They are usually developed by the companies that currently manage the natural gas pipelines and that see this as an opportunity to progressively convert the lines. It is also considered a way to create a "virtual" demand of hydrogen in order to increase the volumes of hydrogen production, and thus the hydrogen market, while getting the advantages already explained. Whatever the reasons to develop it, the hydrogen injection represent the possible solution to unlock the potentials of hydrogen both in short and in long term.

1.2 Geographic Information System

The study presented makes use of Geographic Information System (GIS) tools to develop and solve the objective. GIS are a variety of instruments developed in the field of geographic science from the 60s and defined by National Geographic as the "[…] computer system for capturing, storing, checking, and displaying data related to positions on Earth's surface."[a]. There are other possible definitions for GIS cause it comprehends theoretical and technical concepts difficult to simply summarize. The one reported give a more operative sight to the instrument. In fact GIS is practically the set of data and software that are used to perform part of or all the functions briefly described above and to implement spatial analysis, combining data with different methods to get new informations. The main end of GIS users is not the numerical analysis of spatial data, but their visualization in the geographic contest they refer to, giving an immediate idea of what these information mean in a certain territory. This concept is applied in different areas, like education, real estate business, telecommunications, natural resources and many others [b]. Some additional information about data and software is presented ahead. It is not an exhaustive description, but presents concepts that can be useful to understand the development of the study.

Spatial data can be collected in many ways (remote sensing, GPS, photogrammetry etc.[c]) and result in different categories: cartographic, photographic, digital data and data in spreadsheets. These collections need to be elaborated to be transformed into appropriate data format, that differ in the way the data is allocated on the space. For all the data they are memorized their positions, using a real projection system that define its geographic location, for example according to the latitude and longitude. That make possible, once data is imported in the appropriate environment, to transform with appropriate functions the position information into one compatible with the reference system of destination. The data can thus be located in the corresponding position and with a proper dimension, that reproduce the real one in the spatial reference of destination. There are two main categories of data set: vector data and raster data. Vector data represent data in the space with geometric forms, like lines, points, polygons. It is a spreadsheet where one of the columns, the *geometry*, contains the informations on where and how represent the geometric form. In the associated spreadsheet, at each form can be associated more data according to different fields. Raster data consist of a continuous grid of square pixel, each of them associated to a value. This grid is allocated over a territory thanks to its reference data, and each pixel is represent the value for the area of territory it covers. The dimensions of the pixel are expressed with spatial dimensions (m, km), and the more the pixel are small and dense, the more the data distribution is detailed. It can be used to display distributions of a magnitude over an area or to display images, of other maps or even photos of the territory. The two typologies of data can be used for different typologies of information. Vector one can be used to represent discrete data in different location, while raster to give a continuous representation on the territory.

Once imported on a software, they can be manipulated with different functions, not all of them available for both the typologies. In a software data imported to be displayed are projected according to a chosen projection, so that they refer to the same one and overlap correctly forming a series of layers. Many instrument of elaboration base their working principle exactly on that: they apply the transformation to the layers according to their relative position, and because both of them refer to the same projection, that should correspond to a realistic coincidence of location. The functionalities that can be apply can vary according to the software, but the basic one remain similar. The tools results from a series of mathematical and geometrical elaborations on the nature of the spatial information [d]. They permit to properly transform the numerical information according to the spatial information. Applying different functions it is possible to perform different elaboration from the starting data, create new data and, most importantly, display them to get additional informations resulting from their combination. This description summarize the procedure called Spatial Analysis, that is not a real established technique, but the application of these tools to obtain significative results. The approach is quite intuitive, and it can be said that the purpose of the elements that compose the GIS is the spatial analysis. It consists on the different operations that can be used to derive informations for a problem that require a spatial description, starting from the problem development to the analysis of result. This has been the case of the current study, and a broader explanation of the procedure is given at the beginning of the Method section.

The choice of the spatial analysis has not been neither original nor casual. It is already used in the energy sector as a way to define resources over a territory [22,40-57], to choose the sites for the potential development of projects [58-60] and for the design of an infrastructure development [61-64]. The studies reported differ for the location they analyse, the sources they are considering and for the specific assumption done in the analysis. They all have in common the use of an information directly related to the geographic locations. Almost all of them analyse the spatial distribution of renewable energy sources on a territory, and is particularly significative because all the RES potentials are the consequence it is considered. Wind depends mostly on terrain roughness and obstacles presence, solar on local weather for sky coverage, hydroelectric for the water bodies and thus for the orography, biomass sources rely on forests. Other energy sources are defined by their geographical location, like fossil fuels, uranium caves and geothermic too, but the one quoted above are mostly determined by the interaction with the territory they are in. Usually they start from environmental and weather conditions, like wind speed, solar radiation, biomasses typologies and coverages, and then a model for the transformation into the energy production is applied. To estimate the values according to location make it possible to quantify the distribution of potential energy production and identify sites for further exploration. The GIS instruments can be used to simply visualize the allocations and extract data, or to use tool for spatial analysis. Resources layers are usually raster, because they display a values that has a continuity over the territory. Part of these data are excluded in different ways: polygons can represent urban or protected areas and lines the presence of infrastructures, other raster can embody territory slope or shape. The use of GIS data and software can also be the source of data for other elaboration, like the optimization of an energy system.

All these studies contributed, in different measure, to the development of the one here reported. But among them it has been particularly important this one [65]. It is the technical report *Potential for Hydrogen Production from Key Renewable Resources in the United States*, developed by A. Milbrandt and M. Mann within the National Renewable Energy Laboratory (NREL) research environment. It will often return as a reference or comparison source in the successive pages, thus it will be recalled as the NREL2007 study. It has been developed on the base of other precedent studies, concerning the assessment of renewable energy sources on the American territory. The objective of the study is to estimate the potential production of hydrogen across the US territory. The resources considered involved in the analysis are wind, solar and biomass. The study date back to 2007, and some of the assumptions and of the values used to model the technical conversion from the resources to the hydrogen production are already surpassed by the fast evolution of the sector in the last 13 years. More than the specific values they has been of interest some solutions not adopted in other studies. In the majority of other cases the raster value for the renewable energy sources was used like that, with a spatial partition of the dimensions of the pixels. This partition guarantee a good description of the distribution, at the level of the original dataset. At same time that level of detail is difficult if not impossible to manage at the scale of big countries, like USA and Canada, if the objective is to perform an analysis at national scale. The NREL2007 study starts from the basic raster datasets, that could be more than one if a unique national dataset is not available. At the resulting unique raster they are applied different land exclusions. The outcome of the exclusion is finally used to transform it in the layer where at each county is associated the mean value of the renewable magnitude within it. It is then normalized to the county surface and peoples, and the final maps for these values are reproduced to offer an instrument for the resources evaluation. The estimation is in that case performed with respect of gasoline consumption by state, so hydrogen is considered as the possible replacement for mobility fuels. The element of the cunty division make possible at same time to use a confront a lower number of values that account for mean local values, and to have a more clear picture of the country distribution than the detailed one. It has also been interesting to consider the normalized value as a parameter of source quality, and also the possibility the use of counties division as partition. In fact it is not only an already available detailed division, but also a spatial framework already used for data characterization on the territory. That made possible to aggregate data on the base of states, that represent a common spatial reference, and confront with those of gasoline consumption.

The GIS is strongly related to Canada. The first GIS informatic system has been the Canada GIS (CGIS), a service developed in the 60s as an instrument to support land use and natural resources management. The public service has been overcome by other services, but it remain an established tradition of informations gathering and use via this instruments. That is mostly related to the potentials of the GIS functions for the analysis of data over a so extended territory. In the energy sector the government, and particularly Natural Resources Canada (NRCan) institute encourage the use of energy mapping, especially in the contest of the communities [66][67]. Federal institutions and departments make available a lot of GIS material, both interactive one for informative purposes or even open data that can be downloaded for the analysis. This study insert in this contest, and how it will be explained in the method chapter, the majority of GIS data used for the study comes from governmental sources.

1.3 Canada

The study analyse the resources availability in the national territory of Canada. For the purposes of spatial analysis it is important to consider the contest in which the study inserts, and first of all to become familiar with the characteristics of the Canadian territory.

Figure 7 Canadian geographic map with Provinces and Territories

With its 9,984,670 km^2 the internal Canadian territory is the second biggest in the world, after the one of Russian Federation. This territory is divided among 13 federal divisions, 10 Provinces (east to west: Newfoundland and Labrador, NL; Nova Scotia, NS; Prince Edward Island, PE; New Brunswick, NB; Quebec, QC; Ontario, ON; Manitoba, MB; Saskatchewan, SK; Alberta, AB; British Columbia, BC) and 3 Territories (e-w: Nunavut, NU; Northwest Territories, NT; Yukon Territory, YT). While Provinces governments are recognised by the Canadian constitution, the Territories one get their power as a delegation from the central government. Within this big surface it is possible to encounter many biomes, geological formations and climates, that become harsher going north towards the Arctic Circle (latitude around 66° North). In fact the majority of population lives in the southern area, with the 75% of inhabitants concentrated within 350 km to the southern USA-Canadian border (8000 km, the longest in the world). The 75% is also the percentage covered by the first three provinces by population, QC, ON and BC. The spatial distribution of human activities is thus concentrated in few areas, and that determines the nature of the Canadian energy system in combination with the distribution of its natural resources and the strict bonds with American market.

1.3.1 Canadian energy system

The country is rich of natural sources, and their exploitation is an important asset for the national economy. The production of hydrogen from renewable energy sources will ideally compete with them in the energy market, and thus is important to understand their current level of production. Using the schemes below as reference (figure 8), it is analysed the primary production of energy (2016 data, from [68]).

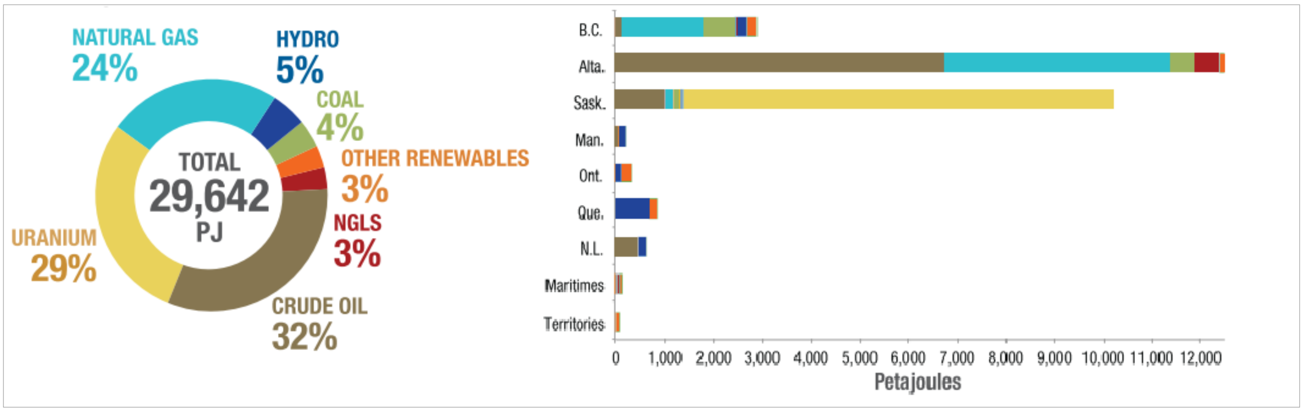


Figure 8 Primary energy production by source and region, 2016 [68]

Crude oil covers the greatest share, almost 1/3 of the total production. The 64% of the oil production comes from the oil sands reservoirs, concentrate in Alberta that is the first producer, and it results in a low quality oil. Its price reference benchmark (West Canadian Select, WCS) is usually more than 10$/barrel lower than the north American reference WTI (West Texas Intermediate). Despite that it is the main source of revenue in the energy sector, representing the 2.8% of the national GDP. Uranium is the second resource, and is extracted only in Saskatchewan. Canada is the 2nd for production and exports in the world, and the 76% of the production is destinated to the markets of Asia (42%), America (41%) and Europe (16%). Natural gas comes third, and the country is the 4th producer and 7th exporter, with the 46% of the production transmitted to the American market. In fact while LNG imports are already in place, exports routes has not being developed so the market completely depends on the American one. That recently create major issues due to the increase of US internal production from unconventional resources, especially among Alberta producers [69][70], that covers the 69% of national production. Coal is a minor resource, while quite an impressive role is played by the hydroelectric, the great electricity source of Canada that is the 2nd producer in the world (10% of global production). Hydro covers 60% of national electricity production(67% of RES), with a series of plants across the country and larger contributes from Quebec. Among the others renewable resources, biomass play the main role with 23% of share among RES. The major contribution comes from co-generation plants at pulp and paper mills, while the remaining regard small dimension power production and ambient heating. Wind (5.3% of RES) and solar (0.6% of RES) are minor sources of power generation, but the both experiencing a fast growth in the last years. To sum it up, fossil fuels represents the 63% of primary energy production, uranium an additional 29% and the remaining from renewables, both for power and heat production. The areas of major production are Alberta, Saskatchewan and British Columbia, with the first covering roughly the 42% of the total. Hydroelectric is the major power source (60%), followed by fossil sources (19%, 9% coal and 10% gas/oil), and nuclear (15%); other renewables produce 7% of power.

The other element that determines the allocation of spatial infrastructure is the energy consumption. For the purposes of the study it is in particular interesting to analyse the natural gas and electricity consumptions spatial distribution (figure 9).

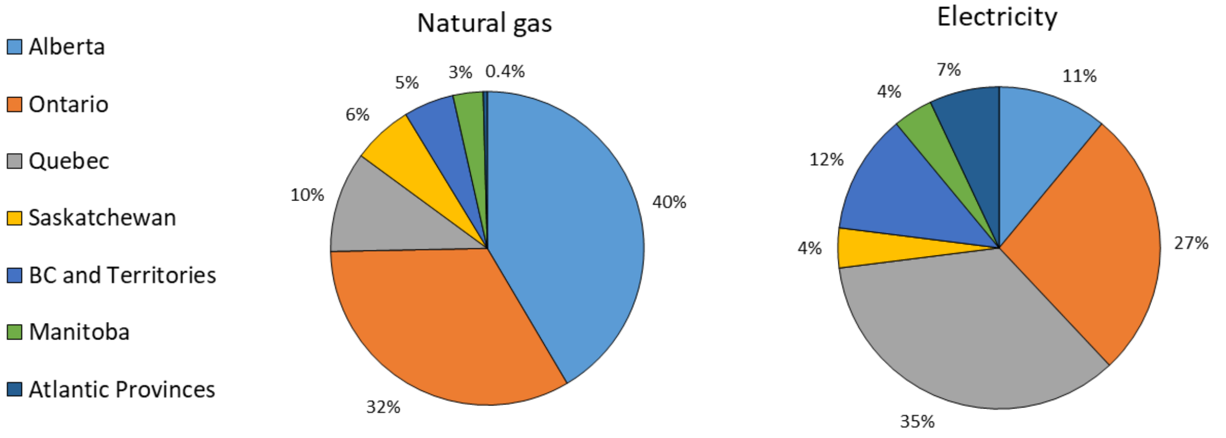


Figure 9 Natural gas and electricity consumption share by region, 2016

The energetic consumption of natural gas is 2518 PJ, the electric one 1785 PJ. The first consumer of gas is Alberta, but the aggregate consumptions of Ontario and Quebec is 42%. That require an import to supply the production that can be both internal, from west to west of the country, or external, on land from US or with LNG from the west coast. It is different the situation of the electricity consumption. The country is able to satisfy its needs relying almost completely on local or internal sources. That determine a wide variety of production solution: while Ontario have a huge production from nuclear (59% of its production), Quebec provide almost entirely by hydroelectricity (95%). Alberta largely uses coal (45%) and natural gas (42%) for the power generation, and that partially justify its large consumption. That does not exactly corresponds to the consumption distribution, but while natural gas production is totally absent in the east, power production is equally distributed and does not require major internal or international exchanges.

The other major player to be accounted in this energy balance is the US market (figure 10). Starting from the electricity exports, Canadian export the 9% of its production, covering only the 2% of US consumption. That can seem small quantities, but this power production exports mostly derive from hydroelectric sources and helps to decarbonize the power consumption of some of the states. While the electricity exchanges are almost only on one direction, the fossil fuels one is more variegated. Canada both import and exports oil and natural gas, and in both cases there is a net export of the sources (considering the percentages applied to the values reported above). But the significative data is that it imports too from the US despite the abundance of sources. While in the case of oil there are more complex dynamics, among which the quality of oil for refining purposes, the gas exchange is the only effect of resources displacement. As already observed they are the east Provinces that need import because of lack of internal production. The imports from US, the 98% of total, covers the 20% of consumption, that thus is covered for 20.4% by imports. The total consumption of west provinces (Ontario, Quebec and Atlantics one) is equal to the 42.4 of national consumption. The consequence is that the 22% of the natural gas consumed here needs to be imported from the east provinces. The shape of the Canadian transmission pipeline follows as a consequence of these resources distribution.

It has been analysed in detail for the work development, and will be reported in the section 2.2.3 of the method.

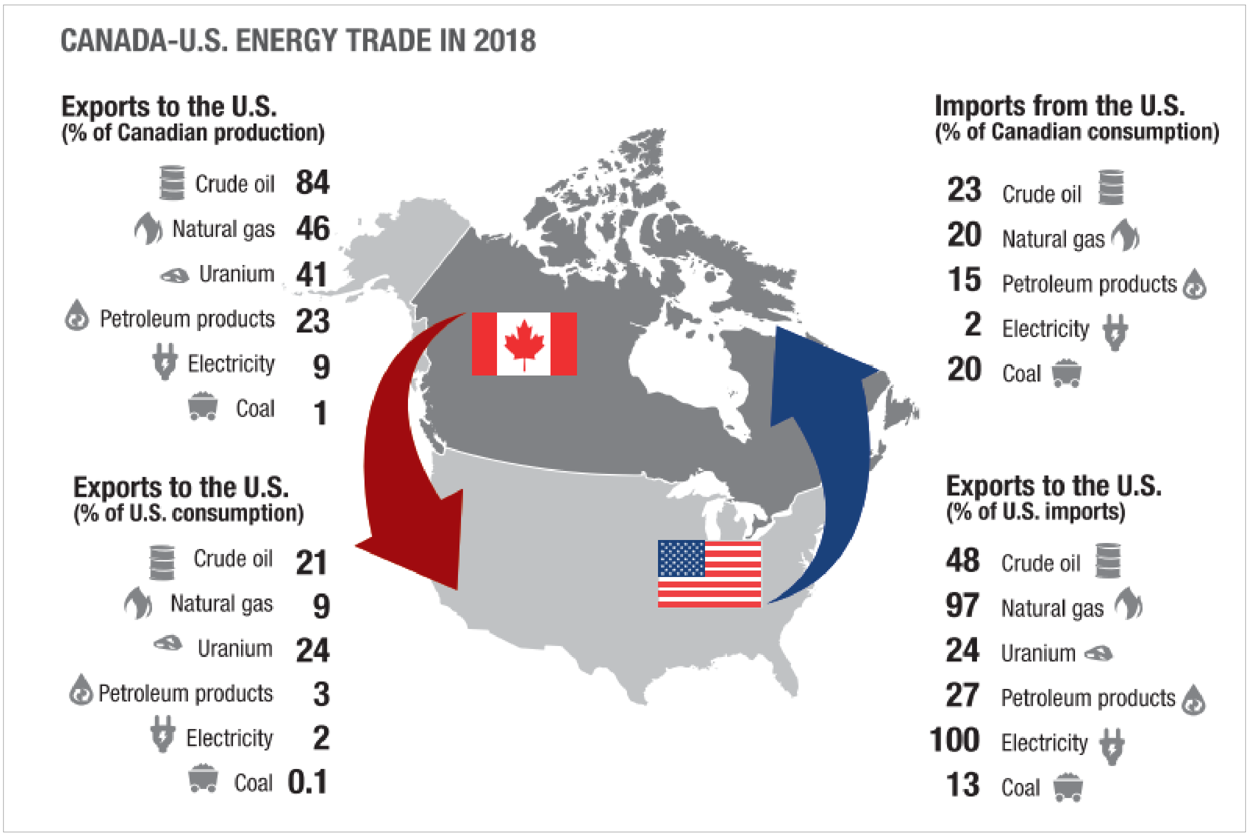
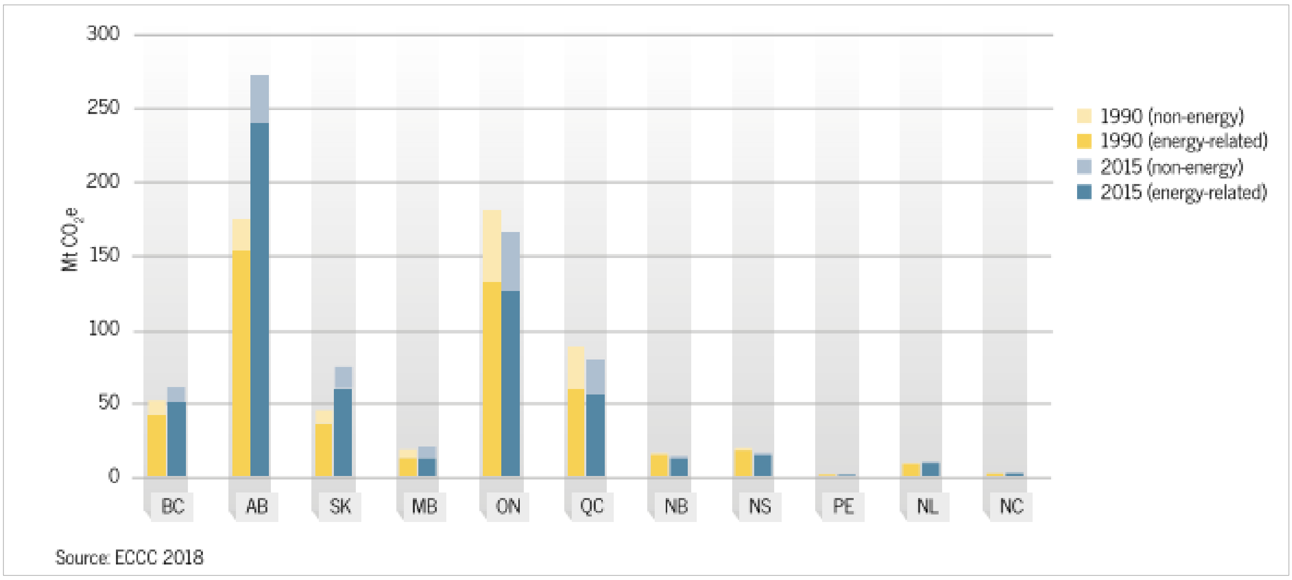


Figure 10 Canada-USA energy exchanges,2016 [68]

1.3.2 Climate actions and hydrogen role

Canada energy system is strongly connected to fossil fuels, not only by the point of view of production, but also of consumption. In the total primary energy supply (TPES) share, they covers the 76% of national uses, only 17% from renewables and the remaining 7% by nuclear. The result of this relation is the high level of carbon dioxide emissions: it was the 9th in the world, with the 1.66% of global emissions. Lower than Saudi Arabia but higher than international aviation. But it is worse the data about per capita emissions, where it results 13th, but first among the G7 countries. Above it in the ranking there are only small isolated countries or the oil producer of the Arabic peninsula. In the emission per GDP, it ranks 16th with a value lower than Kazakhstan but higher than USA. All the indicators, both those of intensity and the absolute one, returns a bad image of the country for carbon dioxide emissions. That accounting only for carbon dioxide, but considering the importance of fossil fuels extraction activities, the overall absolute value are even larger (it ranks 9th also in this ranking). That especially affect the special distribution of GHG emissions (figure 11). Against any previsions, the province with the higher emissions is Alberta. To give a measure of this difference, the increase in Alberta emissions between 1990 and 2015 is higher than the overall 2015 emissions of Quebec. Saskatchewan has emissions comparable with Quebec, but it is less populated and industrialized. The reason for the increase are related not only to extraction activities, and a role has also the dependence of the area on fossil fuels for power production. But fossil fuels production is for sure the major contributor. While industry and power generation activities decreased their emissions in last 20 years, the one from oil and gas production and transportation increased, maintaining the national value almost constant. The power sector performed very well from this point of view, thanks to the phase out of coal power plants. The zero emitting technologies, renewables and nuclear, covers the 82% of production, a share that is exceptionally good among the top emitting and highest industrialised countries. The politics for the reduction of the emissions has now to focus attention on other sectors to decrease the overall impact of the country emissions.



Source: ECCC 2018

Figure 11 Total GHG emission by region, [71]

Canadian climate policy has evolved rapidly since the Paris Agreement, in 2015. The efforts of the government in this direction produced the development of climate related plans in the successive years [71] [72] [73]. This policies set objective and targets both at federal and at regional levels, specific for each province or Territory contest. This measures can be divided in to four main sections: GHG emissions, energy mix and renewables, electrification, efficiency. The first one set objective to achieve for both carbon dioxide emissions and others like methane from extraction activities. The decarbonization of the electricity production requires both additional expansions in the renewable production and the phase out of the fossil fuels plant. Both the practice are already in place across all the provinces, especially in the central one that nowadays strongly depends on fossil fuels generation. A third alternative is the implementation of carbon capture, utilization and storage (CCUS) solutions, and despite the scepticism on the solution affordability the country has on is site two of the few plant application of the technology: one for a coal fire power plant, the other for the capture of carbon from a sand oil processing plant [74]. For what concerns the energy mix, while some province look forward to increase their share of renewable in power production, almost all of them try to face up to the hard to abate sectors, like transportation. Electrification mostly refer to the increase in BEV share while efficiency establish general targets. There is no explicit reference to the heat production, that should be one of the major concern and maybe it is considered as an implicit change to face to satisfy emissions reduction targets. Federal and provincial government established the progressive implementation of a series of taxations to encourage the transition towards energy practice more in line with the climate policies. The most important is the adoption of a carbon tax charged on the fossil fuels producers and distributers, starting from 10$/tonne CO_2 in 2018 up to 50$/tonne CO_2 in 2022. That is an important measure, considering the importance of fossil fuels industry in national energy and economical system, but also the fact that it will hit the final consumers more than companies themselves. Nowadays it has been partially applied in some provinces and the discussions are already in place.

In this contest of transformation of the energy sector, a certain role can be covered by hydrogen. In the current analysis, political targets and energy system forecast it is considered as a possible actor in the advanced stages of energy transition. Its role is usually related to the transportation sector, that as observed needs some of the major efforts to pursue decarbonization. Out of this vision, Canada federal government does not establish a clear hydrogen deployment plan. Also if there are no targets in this direction, it already exist a Canadian hydrogen industry [75] [76] and it is an important actor in the international market. Ballard Power Systems and Hydrogenics are the two majors companies of the sector, and they compete at international level in the sector. They operate in many direction, but their main business areas are respectively hydrogen for transportation and hydrogen storage for renewables integration. That second one is of particular interest for the current case study. Hydrogenics tested systems for both small isolated production areas (tested in Nunavut) and the us in systems integrated with large RES (Denmark). In collaboration with the Independent Electricity System Operator (IESO) and Enbridge, it was commissioned for the development of a power-to-gas system for Ontario grid energy storage. The majority of hydrogen and fuel cell facilities are located in British Columbia, where they are concentrated also the demonstration projects. The experimental and research activity is performed by both private and public actors, while the major source of funding is public, through energy department, federal or provincial government.

The role of hydrogen is thus mostly related to actions in other sectors of interest for the emissions reduction politics. The possibilities related to the hydrogen injection in the Canadian natural gas system has been analysed by Natural Resource Canada (NRCan) institute in a 2017 report [29]. It has been used as a reference to develop the current study with the state of the art legislation, normative and standards on the argument. The wider development in this sense is the federal declaration of 2016 for the development of a Clean Fuel Standard, for the development of Low Carbon Fuel Standard (LCFS). Similar standards are already in place in British Columbia and Ontario for the transportation sector, while government want to include also buildings and industrial uses. The only references are the federal regulations and hydrogen technology codes and standards for the use of the pure gas in the industrial applications. In this phase of the standard development many Technical Comities (TC) are working to establish a unique limit, considering different aspect of natural gas system. Starting from the limitation specific for each of them, they still have not establish a unique reference value, that is considered a premature definition for the current developments of the application. At the same time the possibility to define a common parameter could accelerate the definition of a standard within the context of a national LCFS definition, thus open the way to possible incentives to the solution deployment. The report analyse a series of legislation, codes and standards from other countries, mostly European one and USA states (California, Oregon). These one are then compared with the technical characteristics of the pipeline element and final use devices, if available, and possible conclusions for Canadian system are derived.

2. Method

In this chapter they will be analysed the different steps used to reach the objectives already presented. The exposed procedure describes the logic process that leads to the final results. In the practical realization of the work it has not been followed a proper established technical method. There are different studies used as a reference for the present one, as already stated in the introduction. These studies, analysed through public or released reports, couldn't be used as a straight model cause they don't present a real one and for the reason of the data availability. As already explained this study follows the methods of spatial analysis to obtain information using data with a geographic reference. Spatial analysis approach can be summarized with some general steps:

1. Formulate the problem
2. Explore and prepare data
3. Analyse material and model possible solutions
4. Interpret results
5. Repeat and modify according to analysis
6. Present results
7. Make decisions

The need for this kind of not static workflow is related to the way the problem formulation and the available data combine each other. In the formulation of the problem (1) the purposes expressed by the objectives of the study are developed in a more detailed form to determine the procedure to adopt and the kind of informations required to develop the analysis. The successive step is the gathering of data (2) for the further elaboration in a GIS software. It is necessary to determine which kind data are available from the point of view of both the numerical values and the GIS data format. Informations are often not accessible at the beginning, thus a research in public and private datasets is necessary. In this case phase two is even more important to better understand the found data and to unify them to a common geographical reference. The analysis of the available informations is the base to develop an operative path (3) to find useful outcomes. In the process different functionalities of the GIS software are used to elaborate and combine data, that can be also extracted and transformed with external tools like spreadsheets. When results are obtained, it is given a first estimation of the results (4) and the analysis can be modified or developed to direct it towards more significant outcomes (5). Final results are then presented to answer at the initial objectives (6) and they can be used in a decision making process (7) to provide an information that combines both the numerical and the spatial aspects of a problem.

The solutions adopted in this study result from this approach. The solutions adopted to model the solutions are the result of the choice among different alternatives. The considerations that lead to the final choices are exposed in this report. On the frame of the spatial analysis it has been used a variety of expertise concerning power generation system, RES, hydrogen production via electrolysis, natural gas transmission network. Thank to them it has been possible to elaborate the geographic data into materials useful to fulfil the initial objectives. The spatial analysis approach aim is mostly to provide a qualitative contribute to a problem, and the relevance of the result is related to the capability to combine geographic data to get a spatial information. At same time a robust analysis can results only from a good numerical elaboration, so quantitative results too are significant. With this approach it is possible to combine the manipulation of big dataset with a immediate presentation of the same in the form of the spatial information that is a map.

2.1 Problem formulation

The objective of the study is to find areas of Canada for the production of hydrogen from renewable energy sources and its injection in natural gas network. At the beginning of the study no GIS dataset has been available, so it is developed the initial purpose to determine the kind of data to look at. First it is necessary to consider which kind of RES to involve in the analysis. In the study used as a reference (NREL2007) [77] they are considered three sources: biomass, wind and solar. Production from biomass resources is estimated considering a general biomass gasification process. Biomasses varies in different categories and different kind of processes are available for hydrogen production [78]. Canada has potentially a large resource of biomass in its north savage territories, but as exposed the consideration of this source involves a wide variety of cases both for source itself and transformation methods. Furthermore the use of biomass as a source for hydrogen production, as well as its role for power production, is still under discussion in academic field. The consequence of these consideration is to exclude the biomass from the sources involved in the analysis and consider only wind and solar. An additional source could be hydropower, that already covers a large share in Canadian power system. This source is excluded for three reasons: 1) water potential is already largely used and integrated in the electric grid; 2) it is characterize by a strong spatial constrain that limits the possibilities of the analysis; 3) it is a RES that is easy to store and is already used as a reservoir of power, so there is not the motivation of conversion into hydrogen for storage purposes. For wind and solar sources it is considered the route that pass through the production of electricity and the conversion with electrolysis of water into hydrogen. Solar could offer other alternatives, like the direct use of high temperature heat, but these process are in experimental phases and are not taken into account. Additional renewables that play minor role, like geothermal or tidal, are not considered.

For wind the choice is to consider the horizontal axis wind turbine conversion technology. Wind sources can be both onshore, so located in the inland, and offshore, located in the sea. Both of them are interesting for hydrogen production, but the choice it is to consider only onshore one. The study focus is attention on the sources located in the inland to cross these data with the one concerning the location of the natural gas network. An additional reason is that the cost of power production from offshore wind sources is still largely higher than the one from onshore wind sources, and this make the cost of hydrogen production too expensive to be competitive in short term. There are different possible data that can be used to determine power production. They can vary with the different height at which are measured or derived. In fact the higher they are considered, the lower will be the effect of the ground friction and more regular the wind. It is chosen to research data at around 100 m from the ground, that is a reference height for today wind turbines rotors [79]. Future improvements will possibly lead to higher turbines, but for today standards this is a good reference. Solar offers two main alternatives for power production, concentrated solar power (CSP) and photovoltaic (PV) conversion. CSP processes are not interesting in an are like Canada, whit low temperatures and solar radiation during the year. Photovoltaic is considered as the solar conversion path, and no distinction is considered among the different available technologies because they varies mainly in term of conversion efficiency. Other differentiations can refer to the inclination and orientation of the receiving surface. In that case the available alternatives will be considered, reminding that for the installation of panels a good measure of thumb is to use an inclination roughly equal to the latitude of the location. For the orientation to face the south is considered the best solution.

Two additional considerations have to be done concerning the analysis of RES potentials. The first regards the land exclusion. The study NREL2007 and other GIS based analysis exclude part of the land to take into account the possibility to exploit the natural resources there located. The areas are excluded for environmental, land use or shape reasons, and the exclusion can be total or partial by assuming that only a certain percentage of that surface could be used to install a plant. The method is correct and provide more realistic results, but in this study they has not been excluded areas. The first reason is the difficulty or even the impossibility to find data to use for the exclusion, the second is the objective of the study that has been primary to develop a route for the peculiar case study. Land exclusion is usually adopted in GIS based studies that want to find specific locations, while in the current case the will is to estimate the overall potential of the areas. In a successive step land exclusion assumptions can be done on the base of available data, but paying attention on how local difference are estimated. For similar reasons they have not been performed analysis to differentiate the typologies or the sizes of RES installation, as it will explained in the RES data elaboration section. The second consideration is related to the decision on how to use energy produced by RES. Nowadays it is still debated if the renewable sources should be used for hydrogen production in only in curtailment phases or if plant should run for hydrogen production purposes [2, 9, 80]. The debate is mostly related on the convenience of the options, and while the production in energy waste condition can be considered a storage option its financial sustainability can be questioned. For the same reasons the other option seems still not feasible. For the study purpose it is chosen to consider the installation running for the hydrogen production.

The successive element of the analysis is the natural gas pipelines network. The network can be divided into four sections: gathering, feeding, transmission and distribution pipelines. The injection of hydrogen for the blending with natural gas grid can virtually occur at any point of the grid, with the appropriate levels of pressure. As exposed in the introduction the transmission grid can be more problematic then the distribution one. At same time the interest of the study is to find areas with the potential of large volumes of hydrogen production. Distribution lines are mostly located in urban areas where it is difficult to imagine a large production from surplus or dedicated RES power generation. That is the main reason why transmission grid is taken into account in the analysis. An additional motivation can be the larger possibility to control the homogeneity of the percentage of gasses in the mixture in this section of the network. The gathering and feeding pipelines are used specifically to provide natural gas from the extraction field to the injection points. They serve the delivering purposes of the producers and to inject hydrogen here it seems not feasible. They are in general excluded by analysis and are not object of current experimental activities concerning hydrogen mixing in pipelines.

The two elements of RES and natural gas grid has to be combined together to perform the analyses related to hydrogen injection. Informations regarding RES could be or in the form of power or energy potential production or of weather condition, like wind speed or solar radiation, that can be converted in production data. The second case is more probable, cause doesn't involve technological or land occupation informations. These data can then be transformed into hydrogen production potential. To have a proper spatial analysis that captures the differences across the country a local definition of this potential will be required. This can be granted if RES dataset are already organized according to a spatial division, otherwise a common dataset with country internal spatial division will be required. Once the hydrogen production and demand of hydrogen in grid are determine, it will necessary to consider which function of the ArcGIS software use to complete the analysis.

From this step emerges a more clear problem formulation. It is possible to summarize it in the following table.

Field	Wind	Solar	Natural gas	Spatial reference
GIS dataset to search	Weather or production data for horizontal axis wind turbine at 100 m	Weather or production data for photovoltaic	Canadian natural gas transmission network	Canadian map with internal spatial division
Elaboration	Potential hydrogen production in a reference spatial division	Potential hydrogen production in a reference spatial division	/	Common spatial reference for the RES dataset to define local potentials

Table 1 Problem formulation summary

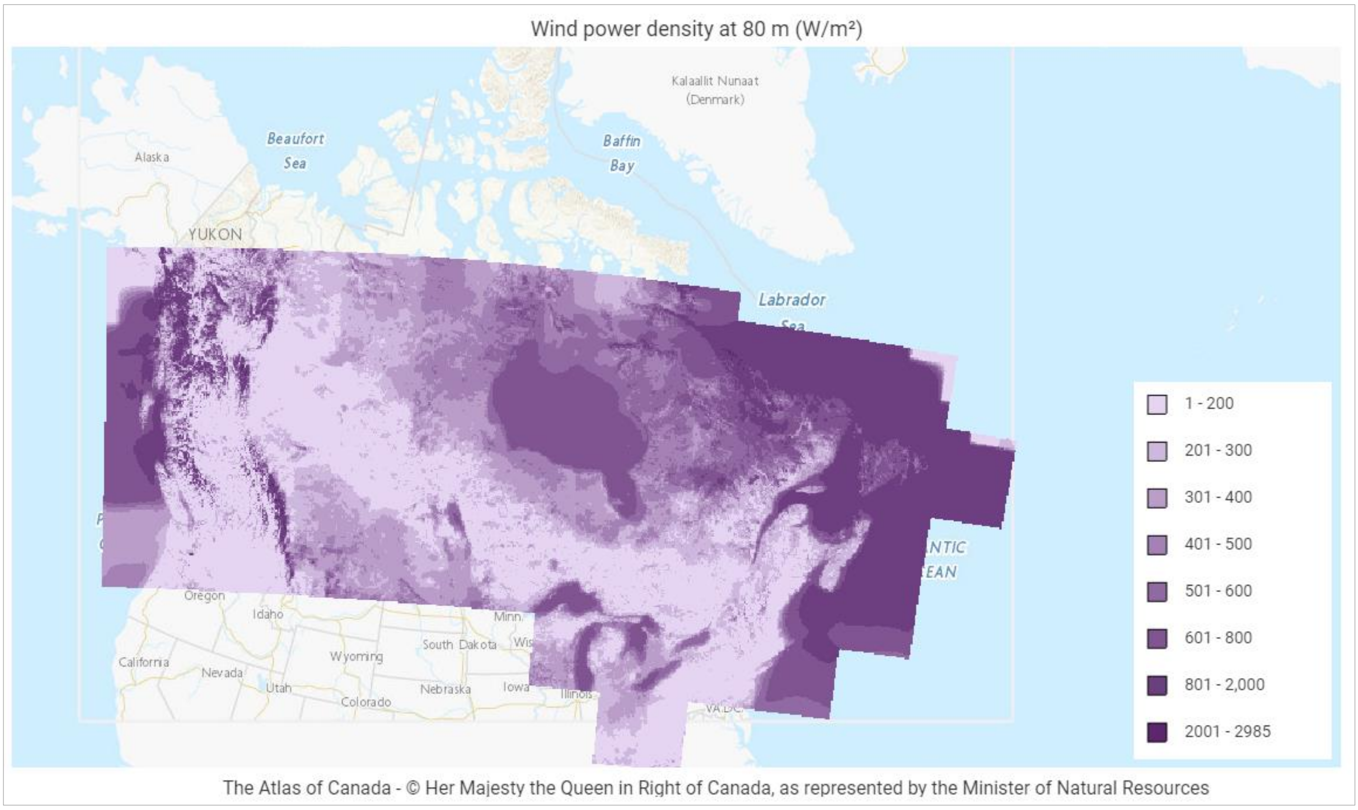
2.2 Data acquisition

The research of data has been conducted mostly on internet, where governmental and institutional websites upload open sources GIS database related to a variety of different informations. In other cases privates make data available for a fee, but this possibility has not been used. The only alternative has been to rely on public data, and starting from them develop a model to get results. In this section they will be only described the dataset chosen for the successive analysis. In case more than one data categories are contained in the data collections, the choice of which one has been adopted to determine hydrogen potential production will be described in next chapter. For what concern the dating of the layers, it has been irrelevant for solar and wind layers if they refers to environmental conditions (with obvious limitations); for all the technical or anthropic related data it has been taken into account its current relevance.

2.2.1 Wind

The data for the wind have been obtained from the Global Wind Atlas (GWA) database [e]. The project has been developed by the World Bank Group in collaboration with the Department of Wind Energy at the Technical University of Denmark (DTU) and is currently at its third version (GWA 3.0). It is a web-based application that can be used to identify areas with a good wind power potential thanks to a variety of data. The idea is to support the early stages of a planning process for the installation of wind turbines by providing free informations for initial calculations. In addition to some online functionalities for preliminary analyses, there are downloadable high resolution maps and the GIS data on which the application itself is based on. In particular can be find layers of the mean wind speed and the mean power density at different height (10/50/100/150/200 m) and the wind energy layers reporting three capacity factors (CF) classified according to IEC wind turbines productors classes (IEC 1, IEC 2, IEC 3). The GIS datasets are available in the form of raster dataset that covers the entire country with a 250 horizontal grid spacing. These data are obtained with a downscaling process, that starting from large-scale atmospheric informations and weather forecast datasets derives the microscale wind climate data. The procedure take into account the characteristics of the local terrain, like roughness and orography, to determine the mean wind speed at higher spatial level of detail. The method has been developed by the DTU Wind Energy [81] and has been validated with 32 measurements on field in 4 different countries, as reported in the website. The power density is directly derived from the mean wind speed via the specific formula. The capacity factors are obtained as estimations for a turbine with the rotor at the height of 100 m and three blade dimensions (112, 126 and 136 m) that fall in the three IEC classes. They have been chosen the data referring to 100 m height for the reasons already exposed. The layers comprehend the data for the off-shore wind too, but during the elaborations they have been excluded from the dataset. The mean wind speed, and so the other informations, is an annual mean value. All data sets for all locations have been updates in October 2019.

The experience of the involved institution (DTU) and the availability of method explanation guarantee the quality of the available data. To have an additional proof of the data reliability it is possible to make a visual confront with a map derived from a different GIS database. It is the map (Figure 12) of the wind power density at 80 m from the Atlas of Canada section of Clean Energy Resources and Projects (CERP) [e]. It is an official governmental database, but it has not been possible to get the data. To perform a qualitative comparison it use the GWA map of power potential at 100 m height (Figure 13). The difference in the height determine a difference in the values, due both to wind speed and air density value included in the power density formula. The CERP map lacks also of the informations concerning the northern part of the country. At the same time the power density distribution and the relative differences between geographic areas, highlighted by the colours patterns, are similar. It is possible to examine common elements that will return in the development of the study. The south part of the country has relatively low potential, with the exception of the terminal extension of the Great Plains, in the provinces of Alberta, Saskatchewan and Manitoba, and hot spot in the mountains between British Columbia and Alberta. The north reveals a general increase of the resources, in particular the norther areas of Quebec, Newfoundland and Labrador provinces and Nunavut territory.



The Atlas of Canada - © Her Majesty the Queen in Right of Canada, as represented by the Minister of Natural Resources

Figure 12 Wind power density at 80 m from [f]

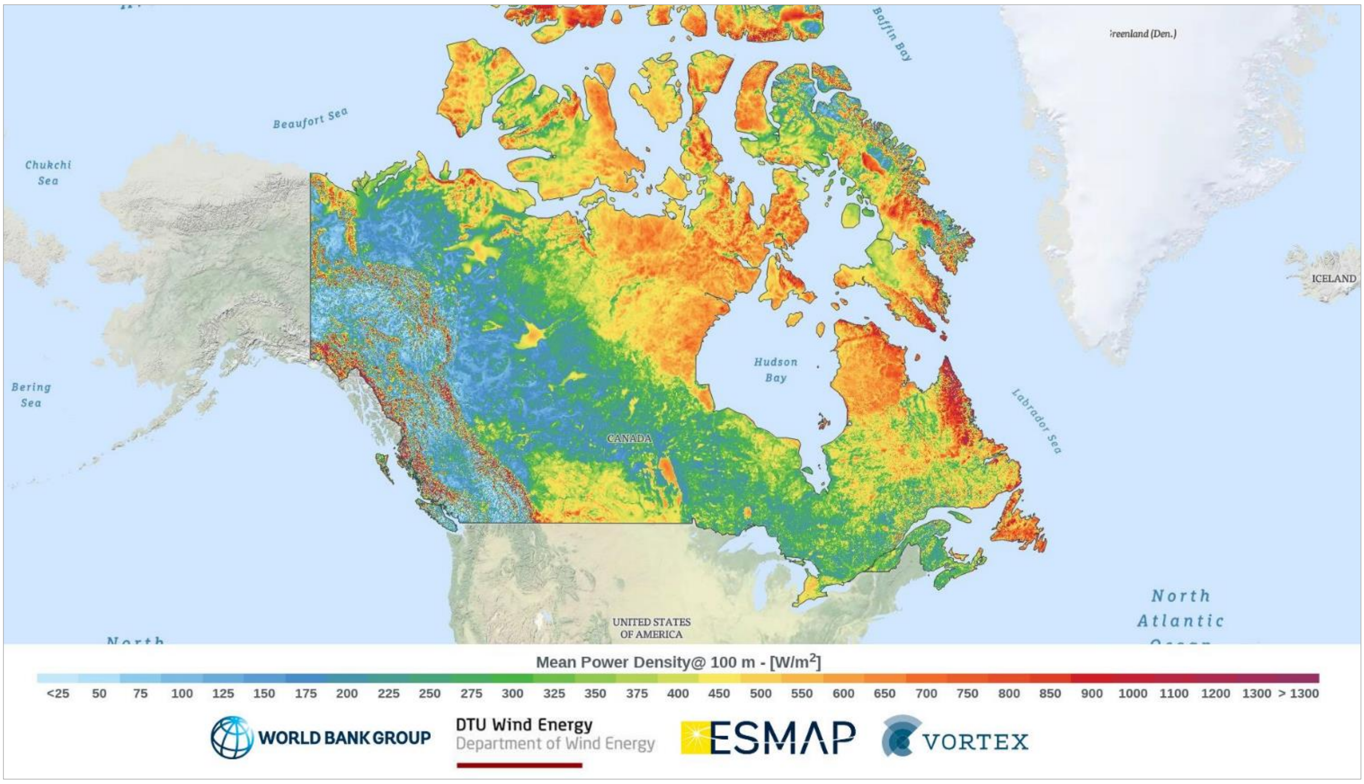


Figure 13 Wind power density at 100 m from [e]

2.2.2 Solar

The data about solar have been obtained thanks to the collaboration with Natural Resources Canada (NRCan) and Environment and Climate Change Canada (2019). They are the result of a study performed to develop maps of insolation and photovoltaic energy potential across Canada [82], [83]. The objective of the study was to elaborate GIS data to generate web-based maps that could be freely consulted to estimate the potential for a PV installation in any Canadian location. The website part of the project is currently not working, but data are available under request to the researchers that performed the study. The database is used to display the solar potential map for the CERP online interactive map [f], but it is not possible to get data from there. They are available two categories of data, PV potential [kWh/kWp] and mean daily global insolation [kWh/m^2]. Each of them is available for both monthly and annual value and for different orientation and tilt angle of the receiving panel surface. As already suggested in problem formulation, they have been chosen the data for south facing orientation with latitude tilt, consistent with the usual installation characteristics. For what it concerns the time period, they have been taken the annual mean data. In fact the availability of only annual average wind data limits the possibility of the study. For the case of solar more than for the wind one it could has been interesting to perform a monthly analysis, specially to estimate the potential of conversion and injection of hydrogen as a way to storage renewable energy in a geographic area where there are big seasonal weather differences. The datasets have been obtained starting from the (CERES) database of monthly mean daily global insolation in 144 Canadian and Alaskan locations. These values has been interpolated over the country and corrected using position (latitude and longitude) informations and precipitation data as a measure of cloudiness (local sky coverage). This process results in the monthly mean daily global insolation across the country, described by a raster layer distributed on a 10 km grid. From these data the PV monthly and annual potential production per kilowatt of installed capacity has been derived. In particular it has been used a standard international value for the performance ratio of grid-connected photovoltaic system without storage batteries [82] to convert insolation values to this one. The last update of the database date back to 2013.

The chosen data can be compared, for a confront and initial examination, with the one obtained from the Global Solar Atlas (GSA) [g]. It is the solar corresponding of the GWA, developed by the private company Solargis that owns and maintains solar resources database. The GIS files are not available for free use but it is possible to freely download maps derived by data. The only common layer available is the PV potential one (figure 14) . The two other are direct normal irradiation and global horizontal irradiation. Both of them are a measure of energy on a surface, but the meaning is quite different then the global insolation and it is not appropriate to confront them. They are compared the PV potentials, that even if are calculated with different assumptions have a comparable meaning. For the data from NRCan archives it is used a map already projected in ArcGIS (figure 15). It can be observed that the extremes of the legend scale for annual PV potential are similar, a proof that data are consistent and comparable. The GSA layer regard only the southern part of the country that is the one with the higher potentials. In particular the higher values are registered in the final part of Great Plains, the same area interested by high wind potential. The central and east part of the country have a medium high potential will British Columbia distribution is determined by the presence of the mountains.

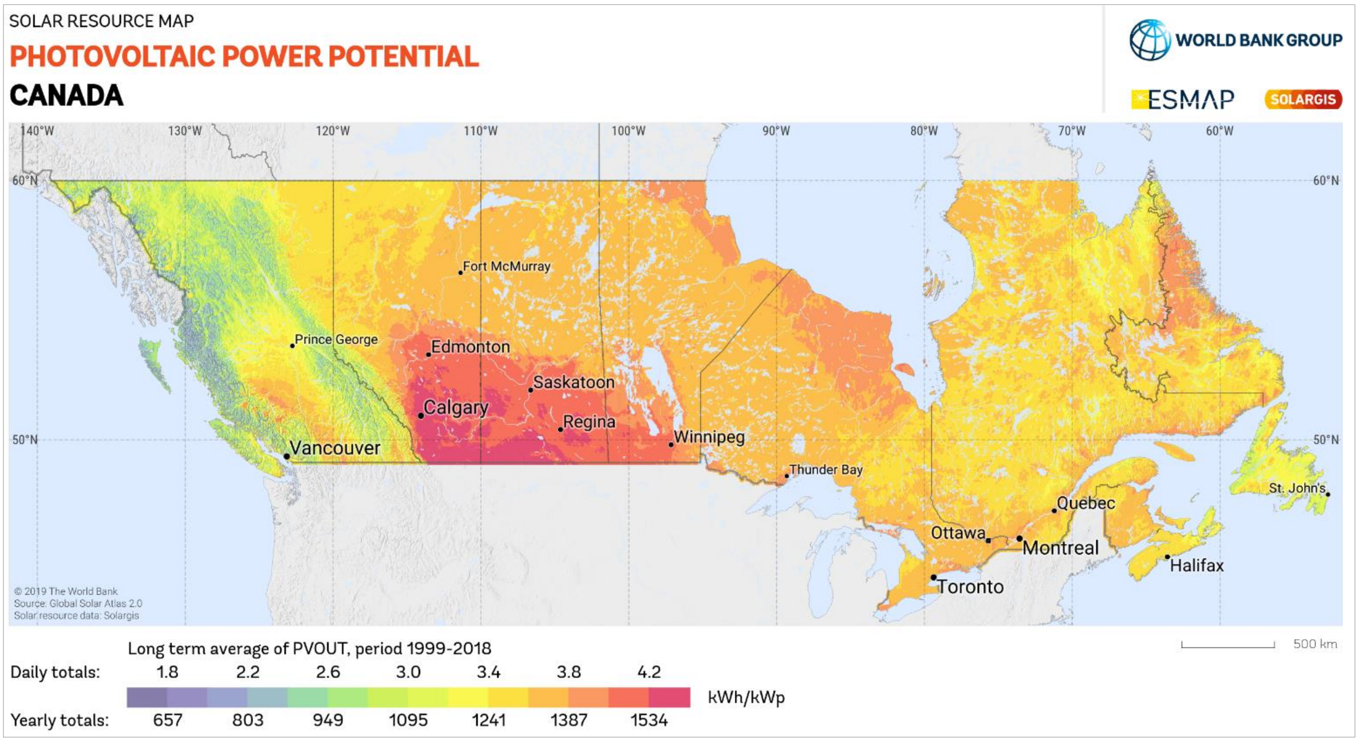


Figure 14 Photovoltaic power potential map from [g]

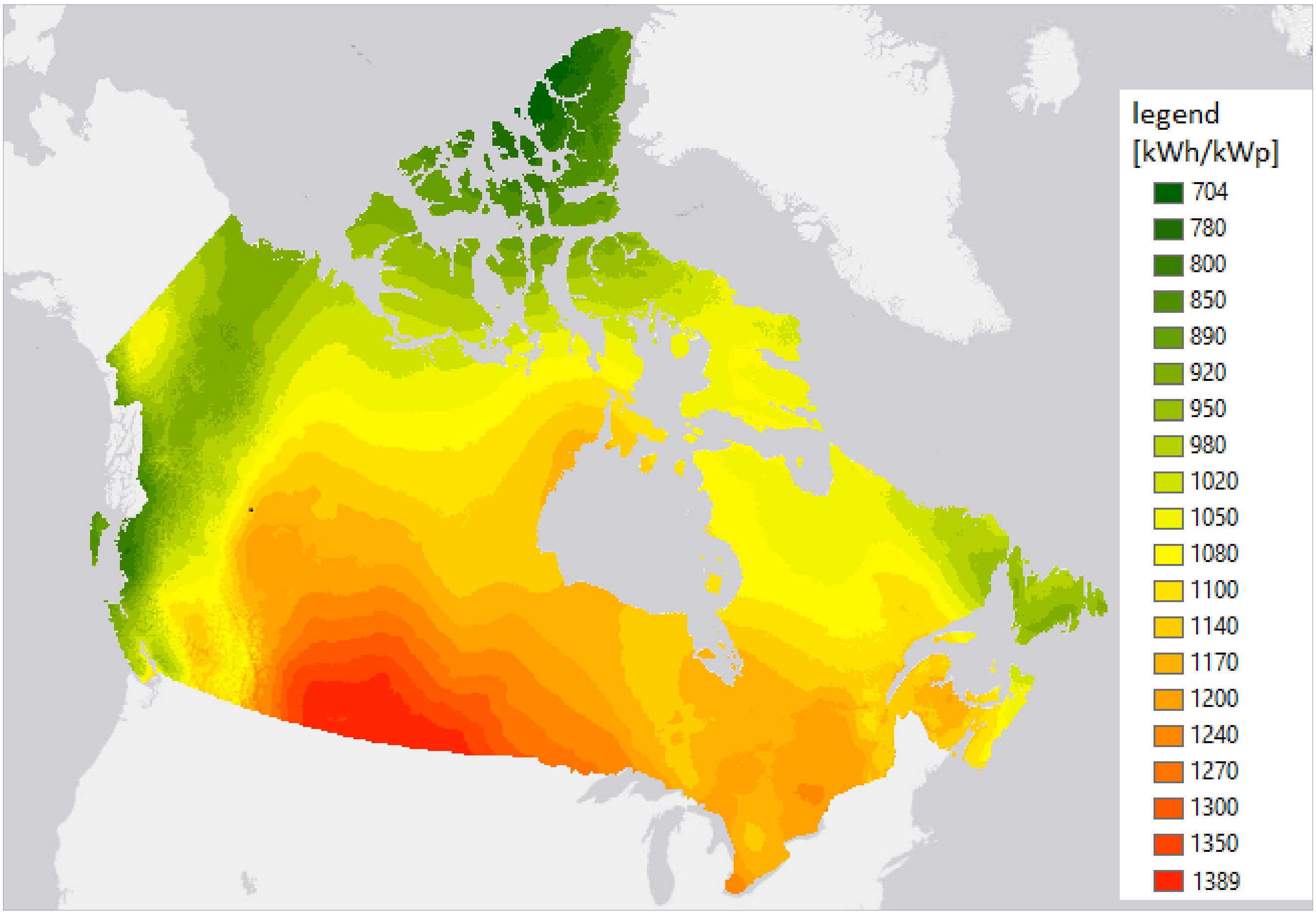


Figure 15 photovoltaic power potential map from NRCan data

2.2.3 Natural gas

The GIS layer for the description of natural gas transmission pipelines has been obtained from the Open Government website, and in particular the CanVec database [h]. It is a cartographical product realised by NRCan as a collection of data that aggregate vector layers from different Canadian institutions. It gathers 60 different topographical features organized in 8 main themes: transport, administrative, hydro, land, man-made, elevation, resource management and toponymic features. The layer of interest is placed among resource management features, inside the data file of mines, energy and communication networks in Canada. Files are divided according to the level of scale detail and the provinces and territories for which they contain data. It has been chosen the file with higher detail (50k) with information of the overall Canada. From the analysis of the layer vectors it is possible to discover that they are divided in four categories according to the transported product: natural gas, oil, multiuse and not identified pipelines. Once imported in ArcMap, they have been excluded both oil and not identified vectors and maintain the other two. The multiuse vectors are maintained because they can be potentially used for hydrogen transportation if they are currently used also for natural gas. The unidentified are excluded because they could be oil one. In any case both of them represent a small minority in the network extension, so their impact could not influence too much the final result of the study. It is important to notice that because of the database is released by the government, it comprehends only the federally regulated pipelines. As explained in the introduction, they fall under this category those pipelines that cross provincial or international boundaries because they cannot be administrated by one provincial regulator. In fact they are regulated by Canada Energy Regulator (CER). That means that not all the existing transport pipelines are described by the layer. More complete and detailed informations are owned by private companies and accessible only for a fee.

To understand how much the used data are complete and if the eventual lack of information is acceptable, it is confronted with a map (figure 16) released by the Canadian Energy Pipeline Association (CEPA). The map is released more for illustrative purposes then for scientific one, so it is not deeply detailed. At the same time it is impossible to control every line branch using a macroscale information, even using other data sources. This map guarantee to be complete from the point of view of the transmission lines extension in the different areas of the country. CEPA states [84] that the majority of its members are regulated by the NEB, thus this map should be very similar to the one obtained from CanVec layer (figure 17). From the confront it emerges the they are very similar, at least in the main branches of the lines. Some minor parts are absent, like Trans Quebec and Maritime, that remain within Quebec borders, or the Canaport LNG, that should be included because crosses provinces border. The CanVec map is interrupted in many points and fragmentated in some sections. While some of the voids are related to the exclusion of the oil pipes, others are missing. It is interesting that some of the lines presented in the proposed status in the CEPA map, are reported in the other one and so are considerate as operative. The first one is dated 2013 while the last update of the database is 2017. The British Columbia line is the Pacific Northern Pipeline, a provincially-regulated pipeline that results in activity in 2019 records of CER.

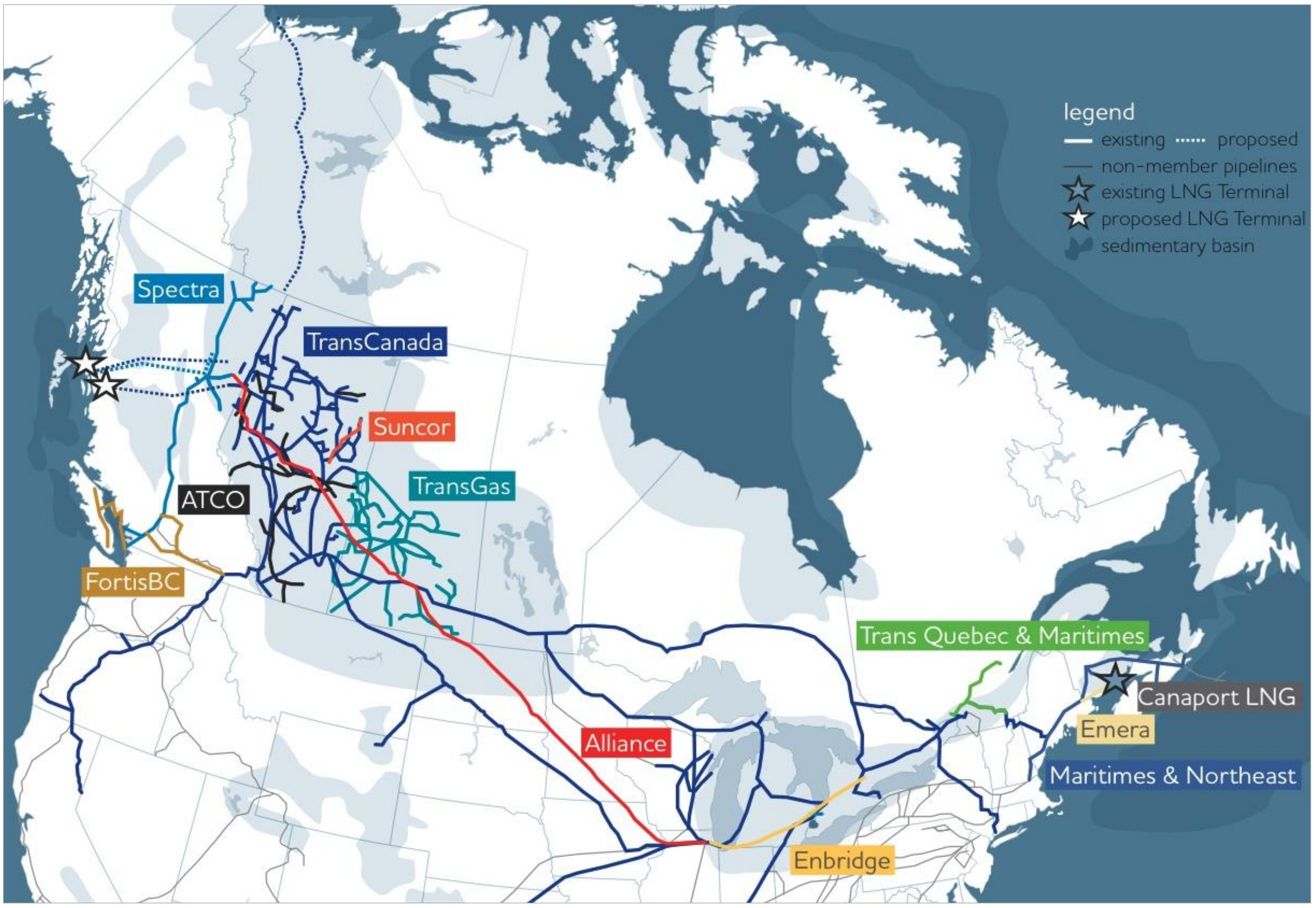


Figure 16 CEPA members' natural gas transmission grid [21]

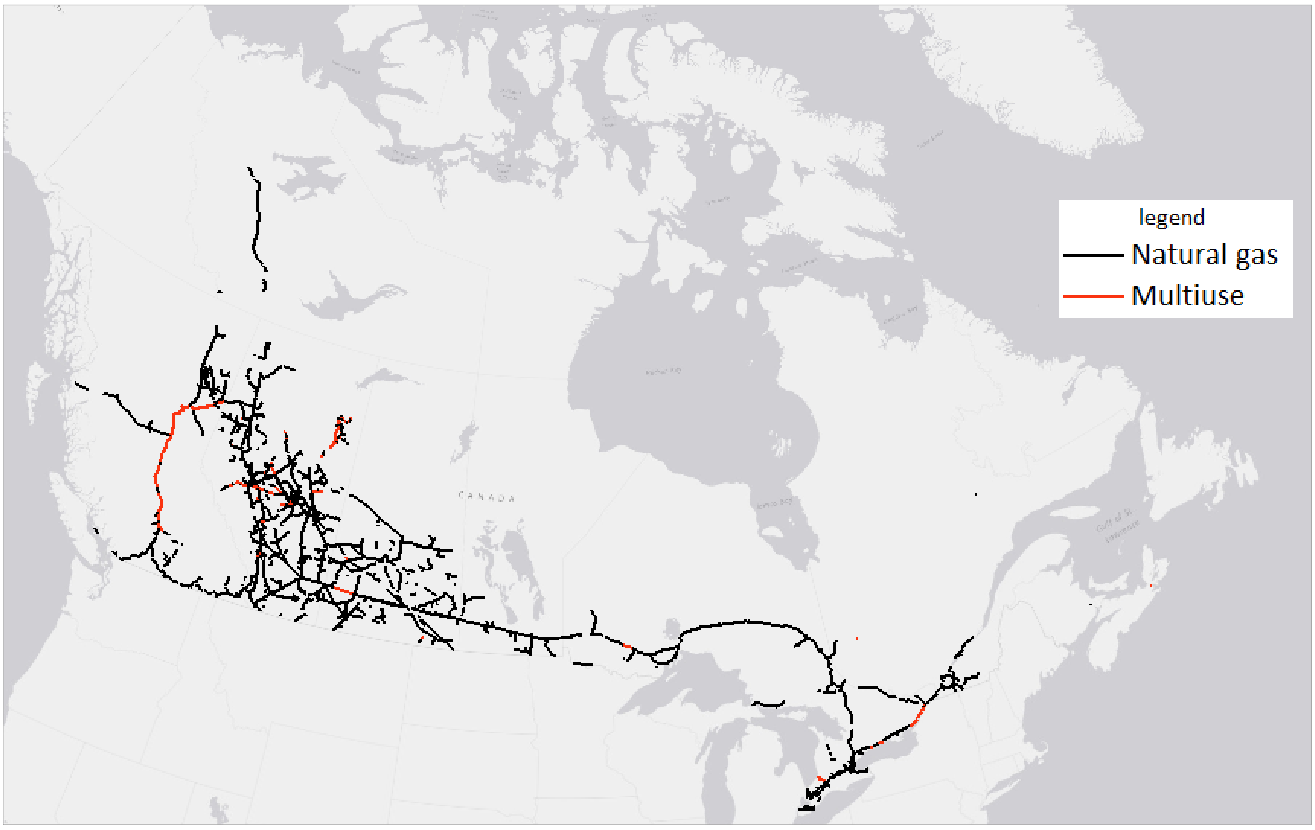


Figure 17 CanVec natural gas transmission grid

The line in Northwest Territories is the Mackenzie Valley Gas Pipeline, a project for that has begun in 70s and despite having received constructions permits has stopped in 2017 for economic reasons. In the same area there is an oil transmission line (Enbridge), so it could also be an error of classification. It has been involved in the study as a way to analyse the potential for the green hydrogen production of the north. For what concerns the qualitative examination of the network, its structure is the result of the Canadian natural gas market. Alberta, British Columbia and Saskatchewan are the main areas for the resource extraction, and they are span by a spider net of pipes that receive gas from the fields. From here it is dispatched to the Canadian market of the east coast, where the majority of population is concentred, and to the American markets of west coast and Midwest. The connections to British Columbia and Nova Scotia (absent in the layer) shores are related to the LNG market.

2.2.4 Spatial reference

The source of the layer for the spatial division file is Statistics Canada (STATCAN) portal. It is the Canada's central statistical office, produces statistics about various topics of Canadian society and conducts a Census every five years. Their data are freely consultable on the online portal, and in addition to surveys informations boundaries GIS files are available too. The boundaries files depict the boundaries of standard geographic areas established to disseminate census data [85]. Their open availability is due not only to the public nature of the institute, but also by its will to encourage analysis of citizens and companies based on a common spatial reference. The selection of this database has been justified not only by this prospect, but also by the variety of available maps. They are classified with different criteria, first of all according to the census year in which they have been produced. The last year with a census has been 2016, so the layer has been chosen among those in the corresponding archive [i]. Here 15 different possible boundaries files are available, each of them capture a different internal division of the country dictated by the needs of the survey. They are organized according to a hierarchy of detail that ranger over different administrative dimension (province, region, municipalities etc) and thematic interest (economic, agricultural, electoral etc) levels. It has been chosen to use the census division map, with a census division being "[…] an area of regional government (such as a county or a regional district) or an area treated as equivalent for statistical purpose" [85]. In the layer file the census division are categorized according to the provinces and territories of belonging, and each of them is identified by a unique code. That classification will be useful in the successive steps for an easier manipulation of the data. The layer is a vector that describes the partitions with polygons. These will be used as a base where to project or attach the data of RES potentials. Once deployed in this common base, these data can be crossed with the informations of the natural gas transmission lines layer to find the areas that could be more interesting for the production and injection of hydrogen.

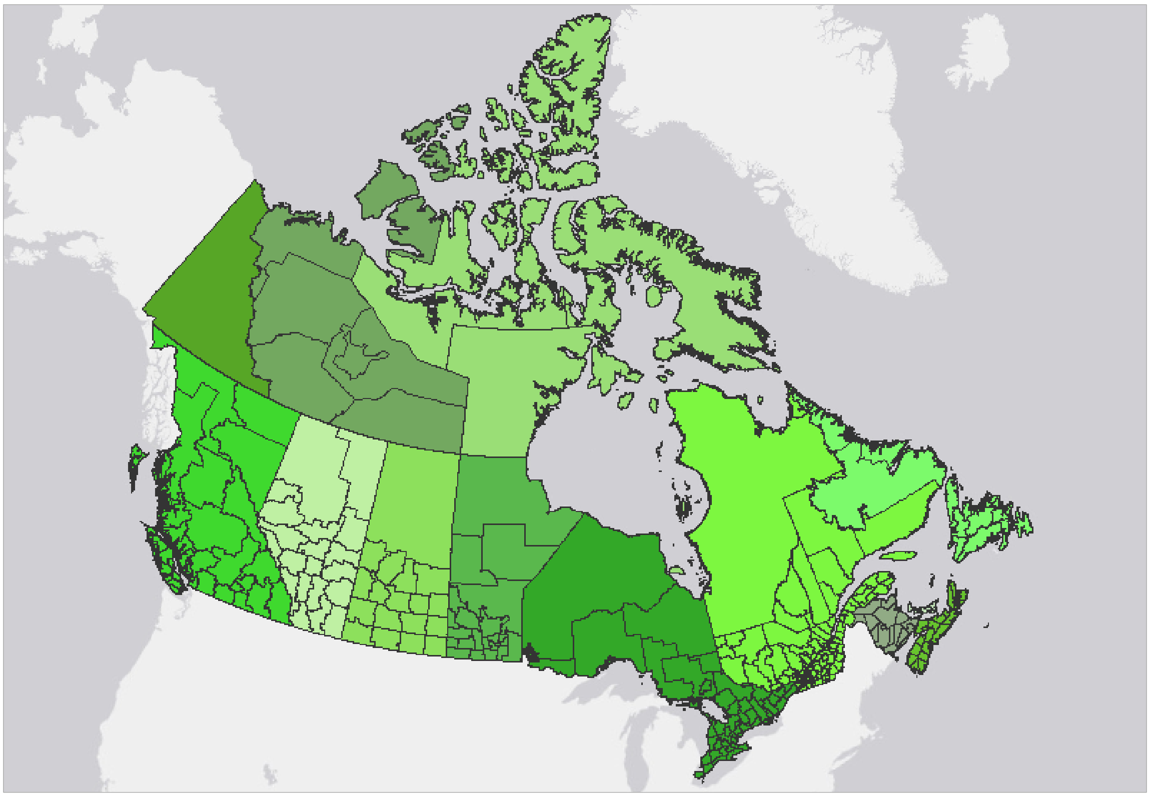


Figure 18 Canada census division map [i]

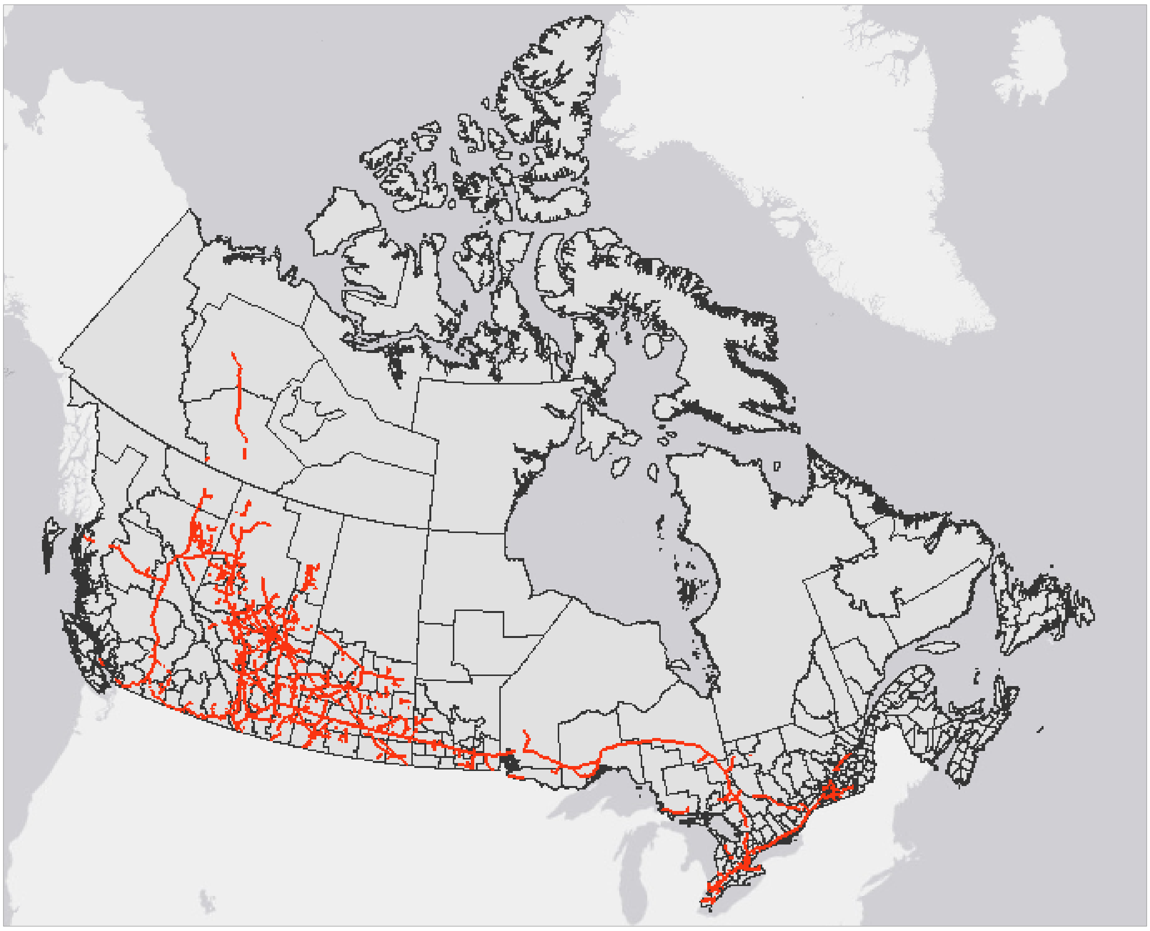


Figure 19 Census division map with natural gas transmission network

To understand the reason of this choice let's analyse the map (figure 18) obtained from the layer, in the light of the observations done for other three maps. Canada is divided in 293 census division areas, but the partition spreads across the territory in a non-homogeneous distribution. The zones in the south of the country, and particularly in the east, are divided in tiny surfaces (49 zones for Ontario, 98 Quebec, but their respective west and north parts are represented by only 1) while the huge north is represented by few divisions (6 Northwest Territories, 3 Nunavut, only 1 Yukon). This description is unequal from the point of view of territory, but it is appropriate for the census survey because of the way Canadian population is distributed. In the south east they are concentrated the majority of inhabitants in the areas around the big cities (Toronto, Kingston, Ottawa, Montreal), while from the west Ontario to the west coast there are only rural areas with minor population density. The north is largely unpopulated with the exception of small communities. For the study the choice is a compromise: the lack of detail in many areas will determine the impossibility of an appropriate analysis of their hydrogen potential production; however from the overlap of the this layer with the natural gas one (figure 19) it can be notice that almost all the areas crossed by the lines have a good level of detail. They differ in the way described above, but the division can capture their specifics. This is not a case but related to the way the energy infrastructure is related to the productive and consume dynamics of the nation. To look at a layer with a tinier division in regions that are far away from the pipeline would have been useless for the ends of the study. The census division layer has a good but not too packed level of detail, and it is in the middle of the administrative divisions hierarchy. Other files go down to the level of single municipalities (but following the same principle already described of aggregation for low populated areas). It could be interesting to analyse the potentials in smaller areas, but the study want to capture the potentials of broader regions in the national scale. To use a tiny division will provide more informations, but they will be diluted when reported at larger scale.

2.3 Data elaboration

The study proceeds with the transformation of the data to find results. To develop a model for the elaboration of informations, they have been combined the various analyses performed on the gained files. It has been important to consider both the qualitative aspects, so what to derive from them, and the operative path, to understand how the files could be manipulated in the GIS software to obtain certain results on the basis of the layers typology and structure. The model has been developed during its realization and what is reported is a practical sequence of the steps performed to reach final results. Many papers and reports has been used as reference for the analysis development, from the one that has inspired the study [65] to many others that use GIS methods and tool to estimate RES potential in different areas of the planet [40-43, 47-50, 54, 55, 58, 60, 77, 86-92]. At the same time the solutions adopted in these cases have mostly not been feasible, both for the difference of the data and for a lack of informations, or have not been appropriate to the kind of solutions researched. During the development of the work they have been used also other sources of informations and methods in the field of renewable energy sources potential estimation. What results is an original way to process the available data and get final results.

The software used for the study is ArcMap version 10.6, part of the ArcGIS Desktop suite. For the settings of the program it has been used the geographic projection Nad 1983 Canada Atlas Lambert, used for the Atlas of Canada and by NRCan and appropriate for the whole Canadian territory [j]. It is a coordinates system centred in the Canadian territory, so it is optimal to represent with the correct proportions part or the entire national territory. It represents the reference layer projection for the four maps used in the study, that will use a common projection to perfectly overlap their spatial informations about positions in Canada. All the maps displayed in this study have been realized with ArcMap 10.6 and have been represented in this projection system. The representation of the Earth surface with that projection appears like that (figure 20)

Figure 20 Earth surface representation with Nad 1983 Canada Atlas Lambert projection

The first elaboration performed in the software has been the transformation of the wind and solar layers. As already exposed they are both raster layers, with a different dimension of the pixel grid size depending on their origin. They cannot be easily use for further analysis without a transformation from their current structure to one that makes available their data in a spreadsheets form. Additionally it is necessary to elaborate to get a common spatial distribution for the successive analysis, possibly on the base of the census division layer. For this purpose it has been used the ArcMap tool Zonal statistics as Table (ZST), that is part of the Spatial Analysis toolbox. The function summarizes the values of a raster within the zones of another dataset and reports the results to a table. They are considered zones all the areas that have the same value in the input dataset, and so that one can be both a raster and a feature or vector layer. When the raster and the other dataset are overlapped, the value of the raster is summarized within the zone the correspond to the dataset element that overlap the raster. In the table they are reported a series of values: value, count, area, min, max, range, mean, std, sum, variety, majority, minority, median. It has been used this function, inserting as raster both solar and wind layers of interest and as dataset the census division layer. Each division is characterise by its unique code (CDUID), so it is identified as a single zone and all the raster values contained within it will be summarized in its section. The value of interest for the purposes of the study is the one contained in the "mean" field, the average of all the raster cells that belong to the same zone. Because of each pixel have the same dimension, it can be considered the mean value of the input raster within the single census division. Once the table has been obtained, it is possible to use the Join function to attach the table to the census division layer. The Join function combines the data table of one element (a feature or a table) to the one of another one, resulting in the extension of the second with the elements of the first one. The criteria for this operation is to associate the common elements according to a chosen field for each table. In the current case, the table resulting from the ZST tool is attached to census division vector using the CDUID field, presents in the ZST result under the field "value" that reports the value that characterised each zone.

The effects of the procedure for the data elaboration are displayed by the maps below (figures 21 and 22) of the raster and the resulting vector for the PV power potential layer, already analysed in the data acquisition section. The colours scale of the two maps is not perfectly equal, but nonetheless it is possible to appreciate the effect of the transformation. First of all the use of mean value determines the decrease of higher values and increase of lower one for the effect of mixing with other data. When this dynamic occurs within larger divisions the result is the loss of the local level of detail. The effect is evident in Yukon, in the Hudson bay shores of Northwest Territories and in Newfoundland, but also in the south area of British Columbia, in north Saskatchewan and west Ontario. This outcome is particularly significant southern areas, that as already considered can benefit more for being crossed by natural gas transmission lines. Relatively small areas that could have result in hot spot of interest are lost. At same time this diluted information is not completely useless: it contributes to rise the average value of the zone within it is contained and so to make it more interesting for hydrogen production. It is a good compromise from the point of view of the spatial dimensions of this study.

The data obtained contained in the tables of the layer can be exported in a spreadsheet, like Excel. There they can be manipulated for the calculations to get the energy or power output to be converted in a hydrogen potential. Before to proceed with the calculations it is better to understand which kind output can be expected so to focus the work efforts to get a compatible typology of results from wind and solar potential calculations. First of all both datasets report annual mean values. That suggest to develop the analysis in the direction of the energy potential. The measure of power requires by definition a detailed description of data in temporal scale while only approximate one are available. To derive a mean annual potential is less significant than obtain an annual potential energy production, that is less detailed but nonetheless represent a result consistent with measures and statistics. Most of the studies analysed face the same lack of time detailed data for the reason of availability and management of a data collection that combines the two informations. Another element is related to the nature of available data. Both global insolation and photovoltaic power potential are magnitude related to an energy potential and would be impossible to derive a power value from them.

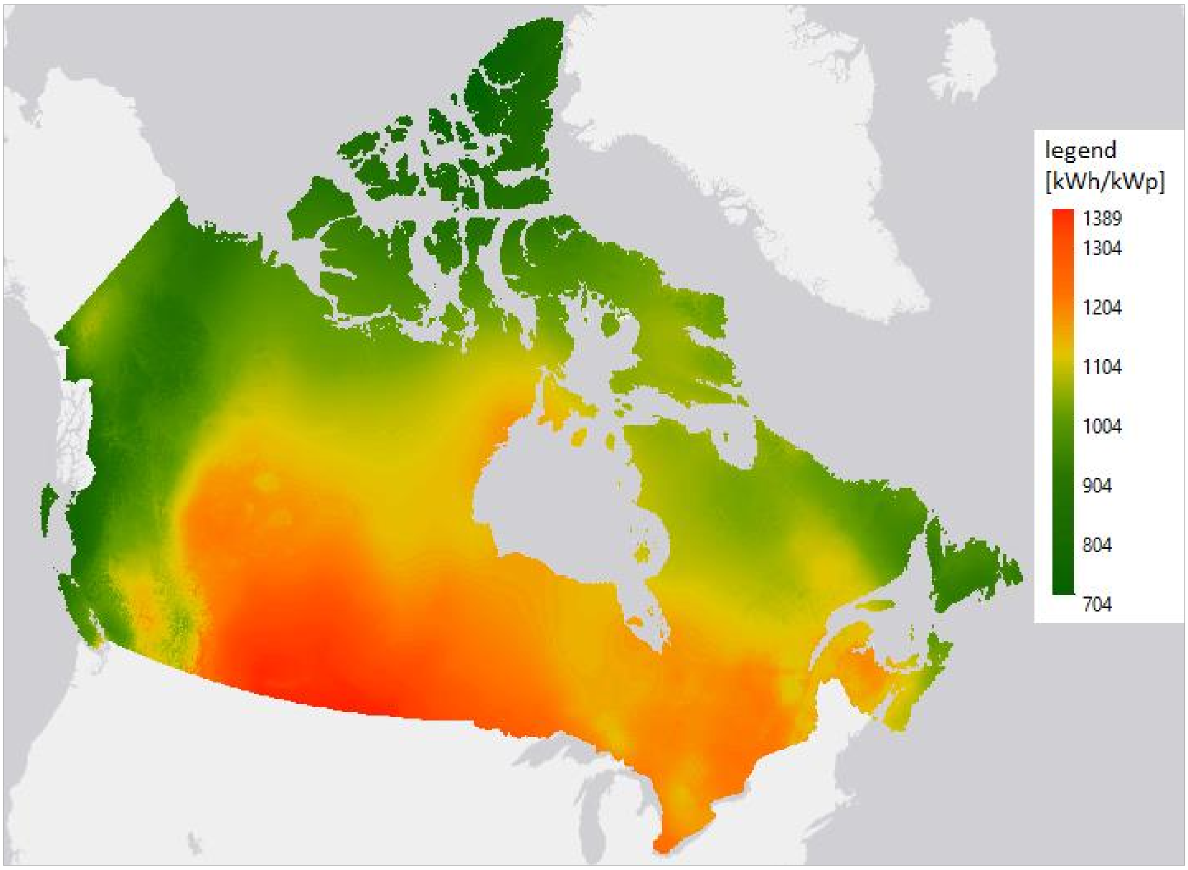


Figure 21 photovoltaic power potential raster

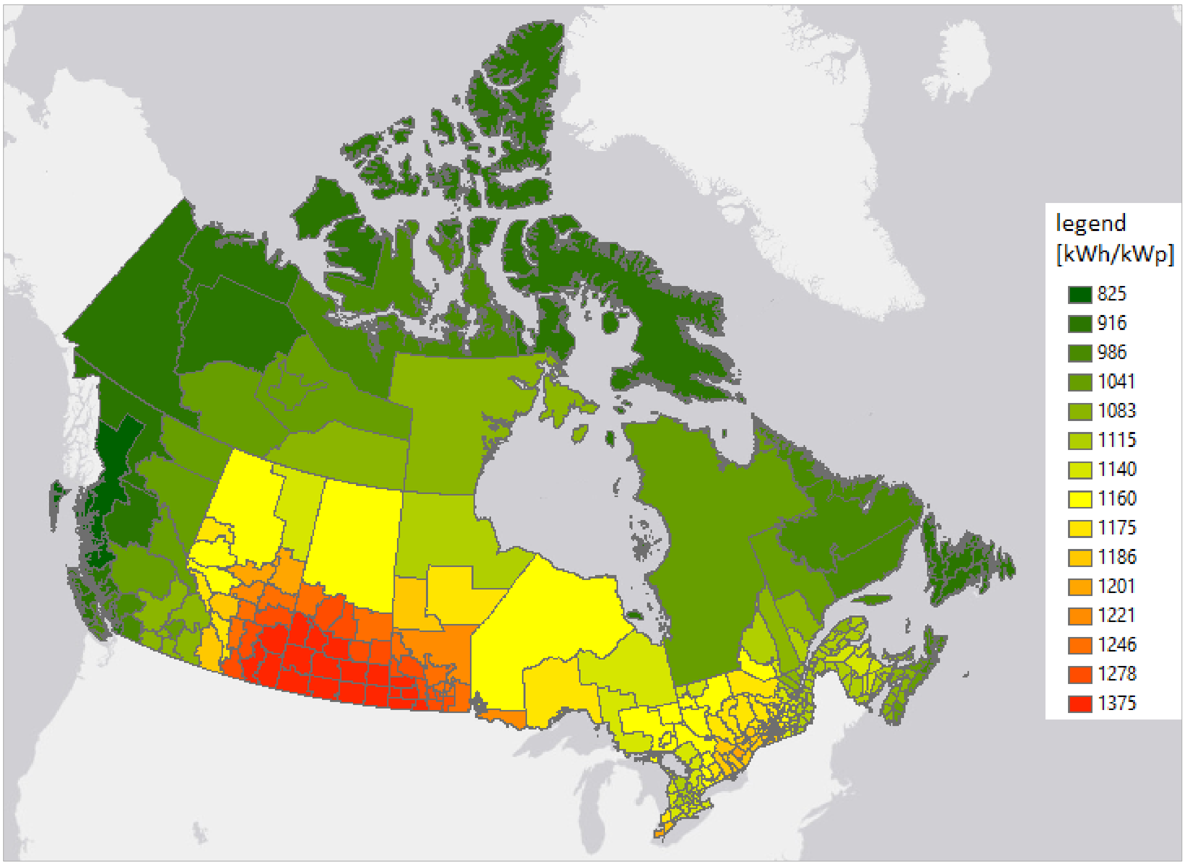


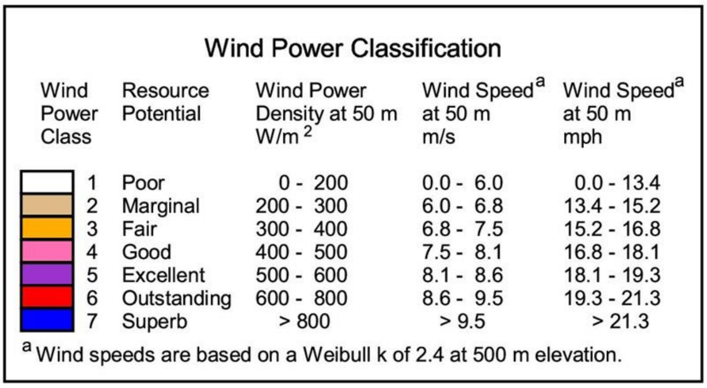
Figure 22 photovoltaic power potential after ZST and Join elaborations

2.3.1 Wind energy density

For the calculation of wind energy density production three different set of data are available: wind power density, wind speed and IEC capacity factor. The first one seems the most suitable but in reality there is no way to directly convert it into a potential energy production. It is a good measure of the effective force of the wind in a certain location, so an indicator for area with good wind potential. No one of the studies considered base its estimation on wind power density and in general it is difficult to find a possible conversion route in literature. The IEC capacity factor represent a good compact data and it is possible to directly derive an energy production value once it has been establish the amount of power to install in a certain area. The International Electrotechnical Commission (IEC) 61400 [93] is a standard regarding wind turbines manufacturing. It classifies wind turbines in four basic classes according to 50 years wind gusts, annual average wind speed and turbulence intensity of the location where it will be installed. The classification determines specific design rules for the turbine to avoid accidents. As a measure of thumb, the higher the class the lower is the reference wind speed of the location. While the data could be easy to use, the choice among the three dataset is not obvious. These data are intended to provide a preliminary information on the potential production in the specific location according to its IEC classification and so to the typology of turbine that would be installed there to follow the standard. What it is require for the study is the possibility to apply a method for the entire Canadian territory. Moreover it is not explained how the capacity factors have been derived from the three IEC class turbines and the meteorological informations. It has been decide not to rely on them, but they could be used for a possible comparison of the obtained results.

It has been used the mean annual wind speed to determine the potential energy production (maps in the appendix: map A1 raster layer, map A2 zonal mean value). The examination of the papers and reports lead to a bunch of possible alternatives. The first one, proposed in these studies [42], [55], [91], [92], is to use the mean value of wind speed to construct the statistical distribution of the velocity. It is known that the measures of wind speed in a location results in a distribution similar to the Weibull distribution, that is possible to derive starting from its mean value. Once the mean annual wind distribution is available, it is possible to use it with the power curve of a reference wind turbine. Using a numeric method (eg Montecarlo method) it is possible to derive the mean annual power output. This data is then used to derive the capacity factor of the turbine in the location as a ratio of mean power and rated power output of the turbine. The method is effective but present some difficulties. First of all the method itself, that derives the capacity factor from the mean power estimation while this is not the actual meaning of the magnitude. From the operative point of view, the difficulties has been related to the availability of a proper wind turbine power curve and the number of localities, equal to the census divisions, for which to repeat the operation. The research has focused on alternatives with simple but consistent methods.

The reference study [65] deals with the conversion using a classification, an approach similar to the one based on the IEC classes from GWA but based on NREL empirical statistics of US wind power [94]. The main difference with the study problem formulation is the height of the wind data used, 50 m and not 100 m, but has been considered as a possible alternative. First of all the zones are classified within a wind power class on the base of mean annual wind speed at 50 m or, seemingly, of the wind power density at same height (figure 23).



Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m ^{2}	Wind Speed ^{a} at 50 m m/s	Wind Speed ^{a} at 50 m mph
1	Poor	0 - 200	0.0 - 6.0	0.0 - 13.4
2	Marginal	200 - 300	6.0 - 6.8	13.4 - 15.2
3	Fair	300 - 400	6.8 - 7.5	15.2 - 16.8
4	Good	400 - 500	7.5 - 8.1	16.8 - 18.1
5	Excellent	500 - 600	8.1 - 8.6	18.1 - 19.3
6	Outstanding	600 - 800	8.6 - 9.5	19.3 - 21.3
7	Superb	> 800	> 9.5	> 21.3

[a] Wind speeds are based on a Weibull k of 2.4 at 500 m elevation.

Figure 23 Wind power classification [65]

Once it has been classified, at each area is assigned a capacity factor according to its wind power class. The assigned values are reported in the table (figure 24), and it can be noticed that it starts only from class 3.

Class	Year	Capacity Factor
3	2000	0.2
4	2000	0.251
5	2000	0.3225
6	2000	0.394
7	2000	0.394

Figure 24 Wind capacity factors [94]

The study consider only areas with wind class higher than 3 suitable for utility scale wind turbine installations, and so capable to sustain the production of hydrogen. The consequence is that all the areas with mean annual wind speed lower than 6.8 m/s and wind power density lower than 300 W/m^2 are excluded. That may seem like a fair assessment, but when applied on 50 m wind speed raster dataset produces that result (figure 25). The red areas indicate the values with the mean annual wind speed above the threshold, the green one those under it. The outcome is compatible with the resulting US wind resources map [65] and excludes almost the totality of Canadian territory. Only few areas, already considered of high wind potential, remain available for the further analysis and this result bound too much the successive analysis. It is largely a limit related to the used data and assumptions. The wind power classification is based on 2005 informations while the classes, and so the wind turbine technology they refers to, date back to 2000 (and are derived from older data). Technology largely evolved in last 20/15 years, and there are previsions for further developments now that RES represent a fundamental energy market [79]. The same choice of 100 m dataset was guided by these reasons. Despite these problems, the method is a valid way to determine the capacity factor and thus the potential energy production from wind. It is based on the empirical observation of the technology behaviour (CF) under certain mean weather conditions (mean annual wind speed), and links the two categories according to a classification. It is similar to the IEC capacity factor, but informations are generalized and there is an explanation of the data sources. The possible option has been to find an archive with a similar data correlation with recent data and referred to wind turbines with rotors at around 100 m height. It has been also notice that a classification determine a rigid transition between classes. The definitive solution that has been adopted changes the classification method by linking mean annual wind speed and capacity factor with a linear correlation.

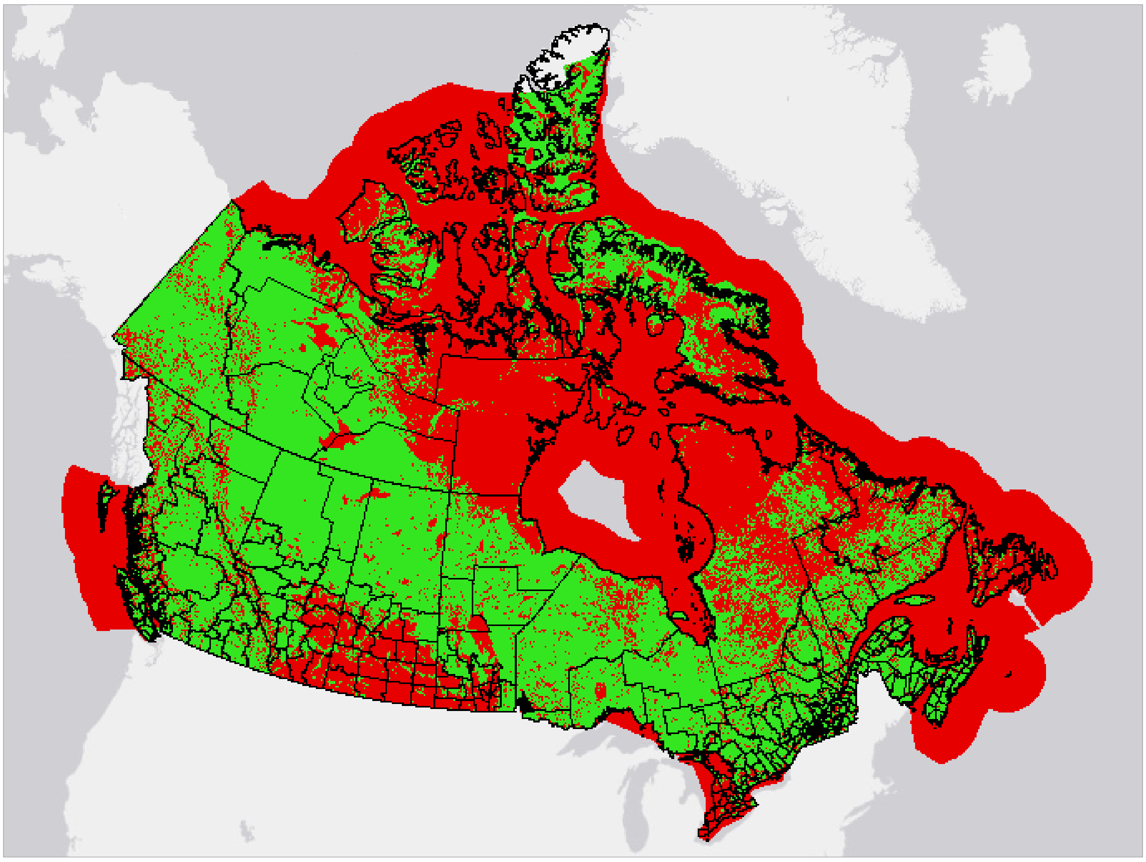


Figure 25 Analysis of the NREL wind classification threshold

That solution moves from the observations performed by different studies ([54][95][96][56]) about the linear correlation that can be observed between the two magnitudes. The fact is partially justified as a simplification of a more complex derived formulation in the study [96], while in the other cases it has been derived with a linear regression from recorded data of US wind turbines [95] or from the power function obtained with a more detailed model [54]. In all the cases the exigence of a simpler model rises from the need to apply it to a broad set of data and the possibility to use a consistent linear function to manipulate them is a good solution. To test this solution it has been performed an analysis based on the available data. Both the annual mean wind speed and the IEC classes capacity factors layers have been obtained from the same source and the second are derived from the first one, as already explained. By consequence it is possible to plot both of them to verify if a linear correlation emerges. Both datasets have been transformed on the base of the census division layer using the exposed procedure, thus they are associate by the common zone. As known the linear nature of the function will not be altered when applied at the average values, getting as outcome the mean values of the results. It is reported the resulting graph (figure 26).

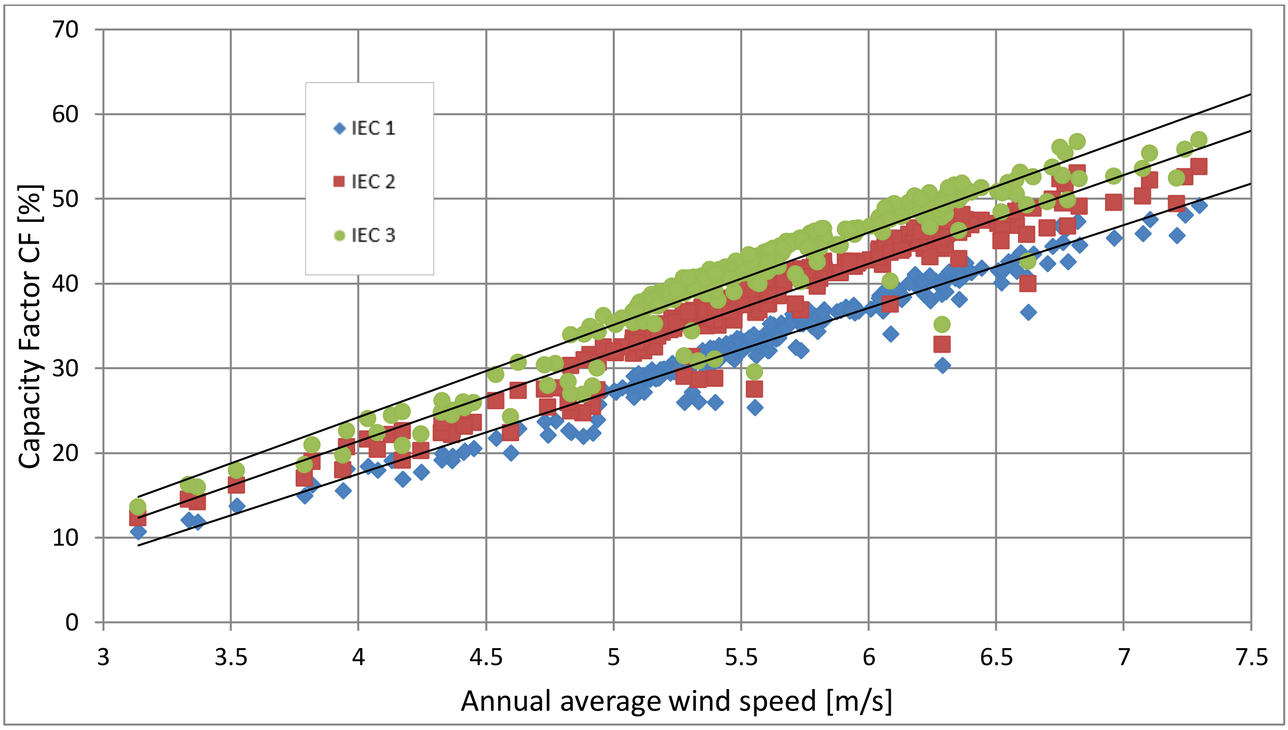


Figure 26 GWA capacity factors average values by zone

The values have a clear linear distribution when correlated to the corresponding average wind speed, as highlighted by the tendency lines. They are modelled and not obtained from statistics that could have generated more disperse one. Nevertheless this is a good proof that the method is consistent, if it emerges also from other approaches.

To derive the linear function used for the calculations they have been used the data from the 2017 Annual Technology Baseline (ATB) [k]. It is a set a modelling input assumptions for the energy sector, released every year by NREL to inform analysis regarding the sector. It has been developed for the US market, but can be considered appropriate for the Canadian one too. They have been used the data for the land-based wind plant production potential. The values are divided in to 10 categories (techno-resource groups, TRG) classified according to wind speed range. For each category are provided a weighted average wind speed and a weighted average net capacity factor. The CF has been determined for the different geographic location using the site specific hourly wind profile and the power curve that corresponds to the most representative wind turbines installed in the US in 2015. The two values are weighted by the capacity of each potential plant the flow in the category, so they can be considered as the most significative of their TRG. To construct the linear function used in the analysis ($y = a * x + b$) the data for average wind speed and CF of the ten classes are reported on a spreadsheet and the two parameters that determine the function have been obtained using linear regression.

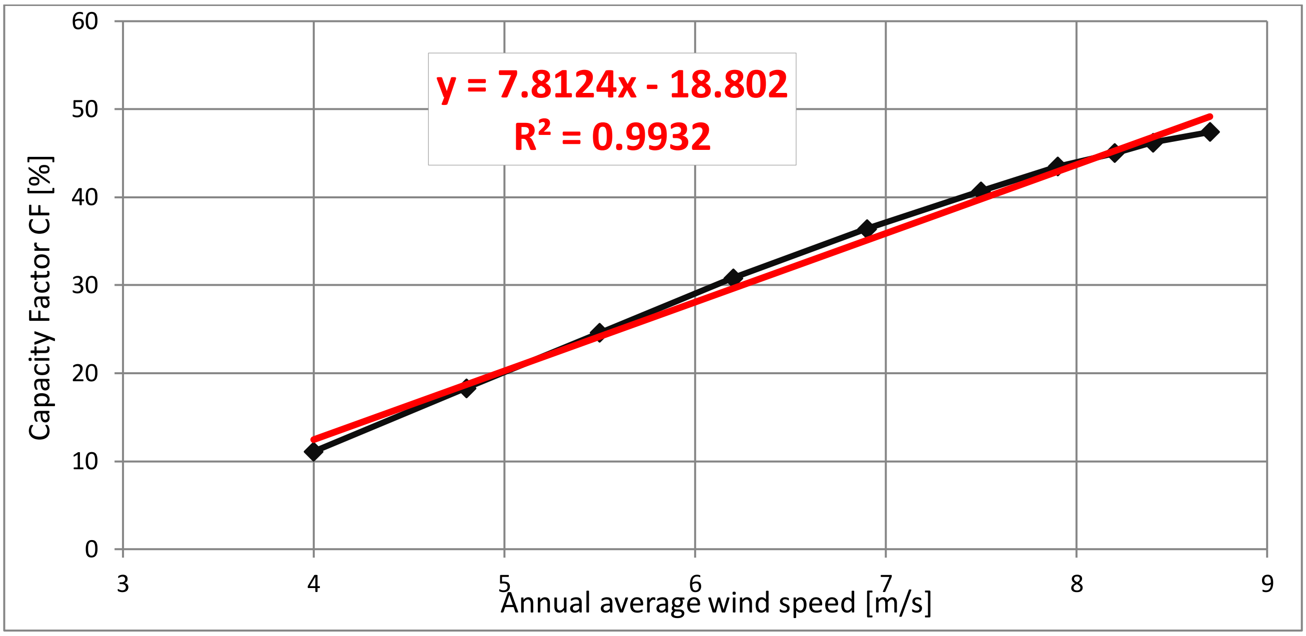


Figure 27 ATB values of capacity factor by wind speed and curve linear regression

The obtained results are $a = 7.8124$ and $b = -18.802$. The negative coefficient b and positive a could have been expected. In fact capacity factor tends to be null at a positive speed like a wind turbine would produce no output at a low level of wind velocity, before the wind stops to blow. The coefficient of determination $R^2 = 0.9932$ proof a good fitting of the regression with the initial data, as it could be expected by the shape of the curve derived from ATB statistics. The obtained curve is also compared with those described by the quoted studies, reproduced using the same sample of data. The same values are applied to the wind class method, used in the reference study, and to the linear functions obtained with the regression from GWA capacity factors.

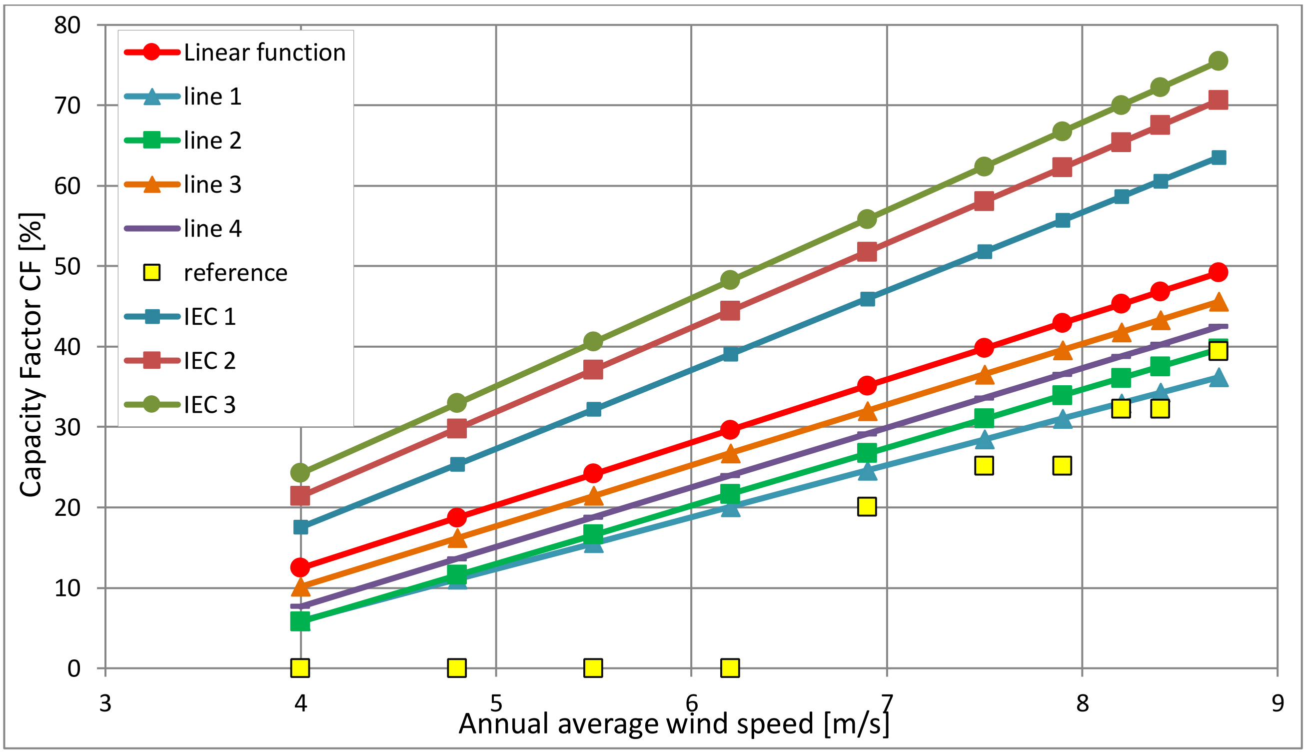


Figure 28 Comparison among different analysed linear regressions

The linear functions of the analysed studies (line 1 from [95] and line 2,3 and 4 from [96]) produce values similar to those from the obtained one, but shifted by a value of CF within 10%. That could be the effect of the wind turbine models and the age of the data used. The outcomes for the GWA derived functions (IEC 1, 2, 3) are much higher, and the difference spread with the increase of the wind average speed. They are based on more recent data, and that could result in turbines with both higher energy yield and designed to work at higher wind speed. The reference study data are displayed only by squares because there is not a real function but system based on categories classification. It is interesting to notice its discontinuity: the values for which it is defined a CF, wind class 3 or higher, are similar or even higher than the analysed cases; but with lower wind classes the result is zero and that, as already considered, would have penalised too much the successive calculations. In the results chapter the GWA, NREL2007 and used capacity factors will be compared on the base of potential energy production.

The method for the determination of the capacity factor has been an important step, and with its application to the dataset of the mean annual wind speed layer it is possible to determine the capacity factor of each census division zone. To get the energy production potential it has been necessary to define, for each area, a value of potentially installed nominal power. The easiest way to determine it is to define a power density for wind turbine installation and multiply by available area to get the installed rated power. The problem related with this approach is that different terrains determine a different power density for many reasons related to the characterises of the location. It is different from the case of land exclusion or limitation, already analysed, and concerns local specifics. It has been decided not to consider these differences, both for the difficulty to construct a complete set of data to describe them, and for the complexity of the modelling to report them in an equivalent way at the census division scale. The solution is to use a constant power density for all the areas and then let the capacity factor express the potential production that can be achieved. The large variety of possible wind power density affects also the reports [97-100] that has been consulted to determine its value. Depending on the chosen pool, the value can range from 0.5 MW/ km^2 to 12 MW/ km^2 and the average value from 0.9 MW/ km^2 to 5 MW/ km^2. It has been chosen to use the value of 5 MW/ km^2, used also in the NREL2007 study that follows the same approach for energy calculation.

At this step all the elements to define the energy density production are in place. It is equal to:

$$E_{\rho,w}\left[\frac{MWh}{km^2}\right] = P_{\rho,w}\left[\frac{MW}{km^2}\right] * CF * 8760\ h$$

The energy production from a certain zone can be determined by multiplying the proper values of energy density and surface. The surface values to use in the product have been determined in the section 2.3.4, where it is calculated as part of the spatial analysis.

2.1.1 Solar energy density

The calculation of the solar energy density has followed a more regular route that the wind one. The two set of data obtained from NRCan database are both a measure of an energy potential and can both be used for the purpose. The annual mean daily global insolation (H [kWh/m^2]) is the measure of the overall solar radiation that surface receive, in particular a surface that face south with a slope equal to the latitude (the extremes for Canada are between 42°N and 87°N for the Artic archipelago's lands, but the max latitude involved in the study has been around 65°N). As already remembered the choice of the orientation and mostly of the slope is related to a general rule of thumb for the installations, in general confirmed as a good choice by more accurate analysis. To determine an annual energy density it is necessary to establish a conversion model for a photovoltaic panel with the spatial characteristic of the described surface. This analysis has been already performed by the NRCan team that developed the layer with *H* data. The calculations result is the PV electricity generation potential (maps in the appendix: map A3 raster layer, map A4 zonal mean value). The model has been analysed to verify its validity and the possibility to use the data for the purposes of the study. The conversion from one dataset to the other is entirely based on one simple equation, valid for the conversion of monthly data:

$$\frac{E_a}{P_n}\left[\frac{kWh}{kW_e}\right] = H * N * PR * 1\frac{m^2}{kW}$$

with *Ea* achieved energy production, *Pn* photovoltaic installed nominal power, *N* number of days in the month, *PR* performance ratio and *H* monthly mean daily global insolation. It doesn't appear any efficiency value and its related to the nature of the *PR* term. The performance ratio represent a measure for the degree of utilization of a PV array. Different effects contribute to decrease the amount of effective energy output from the expected one, like the incomplete surface irradiation or the failure of components in the device or in the system. The performance ratio is a coefficient derived from statistical values gathered on the field to model these losses. For what concerns the effects of the surface temperature for the decrease of the module efficiency, there are different opinion in literature ([101], [102]). In fact it is the result of statistics, so also this effect should be captured. In fact the value largely varies when estimated for different climates. At same time it is pointed out that using a single value for a the whole year will not capture the seasonal differences, a relevant effect if combined with different levels of solar irradiation. In the NRCan model it is considered a unique annual value despite the monthly breakdown used. Canadian territory experience wide seasonal and spatial temperature variations, and the effect could be significative. But because of the problem is debated an mostly based on experience, they are maintained the NRCan assumptions. The performance ratio is defined as

$$PR = \frac{\eta_{achieved}}{\eta_{nominal}}$$

so the ratio between the effective efficiency of the installation derived from its energy output and the nominal efficiency of the pv modules. The value chosen by NRCan as a result of statistics analysis is of $PR = 0.75$. It is in line with the values obtained in other studies, in particular with those related to areas with a climate similar to the Canadian one ([101]–[103]).

The formulation used for the conversion can be derived as follows. The monthly achieved energy is defined as

$$E_a = H * N * \eta_{achieved} * S_p = H * N * \eta_{nominal} * PR * S_p$$

where the H by N result in the monthly solar insolation and S_p is the receiving surface of the panel.

The nominal power can be expressed using the way the η_n is rated by pv modules producers using the standard testing conditions (STC). The efficiency is

$$\eta_n = \frac{P_n}{1\frac{kW}{m^2} * S_p} \rightarrow P_n = \eta_n * 1\frac{kW}{m^2} * S_p$$

Where $1\frac{kW}{m^2} = 1000\frac{W}{m^2}$ is the irradiance with normal incidence used for the test. Composing the initial formulation, it results as

$$\frac{E_a}{P_n} = \frac{H * N * \eta_n * PR * S_p}{\eta_n * 1\frac{kW}{m^2} * S_p} = H * N * PR * 1\frac{m^2}{kW}$$

The values have been calculated for every month, then the summed monthly values determined the overall annual photovoltaic power potential. The product of this potential for the installed nominal power results in the annual produced energy. It can be noticed that this value has a similar meaning to the capacity factor, with the difference that it is expressed as a energy-power ratio. As cf it expresses a difference between nominal and actual energy production by accounting losses, stops and differences of working condition. The biggest difference is related to the weather conditions changes, here captured by the H cumulative that accounts for both day-night cycles and cloudiness effects.

Instead of multiplying for the nominal power, it is initially calculated the solar energy density with the product with the solar power density. As already discussed for the case of wind potential, it has been decided not to distinguish among different areas for the limitation of the installation density. Consulting different studies([99], [100], [104]), it has resulted that the solar power density range between 25 W_e/m^2 and 4 W_e/m^2 and 5 W_e/m^2 is generally considered a the average value for plant located in north America. While in the wind farms case the variety of available values could depend on the different typologies of installations depending on location, for the solar plants the design tends always to pack the higher number of arrays wherever there is a suitable area. It is used the average value of solar power density, and with this data, the energy density is derived from photovoltaic power potential data as follows.

$$E_{\rho,s}\left[\frac{kWh_e}{km^2}\right] = P_{\rho,s}\left[\frac{W}{m^2} = 10^3 * \frac{kW_e}{km^2}\right] * \frac{E_a}{P_n}\left[\frac{kWh}{kW_e}\right]$$

A possible alternative to this route could has been the one used in the NREL2007 study. The mean daily global insolation value is transformed in the energy production using a series of factors and multiplying by the available area of the available land. Starting from the overall surface, it is assumed that only the 10% of it could be deployed for pv production purpose. Within this area only the 30% would represents the effective pv modules surface. The overall monthly received energy is obtained as

$$E_{tot}[kWh_e] = H\left[\frac{kWh}{m^2}\right] * N * S_{effective}\,[m^2] = H * N * ((S_{tot} * 0.10) * 0.30)$$

The annual value is obtained with the summation of the monthly values. To get the energy transformed by the module into electricity, it is assumed an overall efficiency of 10%. This is a value generally assumed as a good estimation of the pv modules efficiency [99]. The assumption may be good and appropriated, and the two methods both use constant factors to convert the global insolation. In particular, considering the common monthly value $H * N$ and assuming a total surface of $1\ km^2$, to calculate the monthly energy output $[kWh]$ the first route will multiply the value for a factor 3750, the second for a factor 3000. The final results will clearly have a the same order of magnitude and almost the same value. The difference is that in the NRCan study the choices are justified, also if they can be improved. In the NREL2007 the assumptions are not clearly justified, thus the fact that results are so close could be a case as the proof of methods convergence to same outcomes.

2.3.3 Hydrogen production density

The energy potential annual production of solar and wind for each zone has to be converted into potential hydrogen production. As already discussed the best way to determine the potential outcome from an electricity source is to use the characteristic polarization curve for the chosen electrolyser technology. It has not been possible to follow this route both for the lack of time significant GIS dataset to be used and for the material difficulties to store and elaborate them. Once zone with hydrogen production and injection potential will be found, the successive analysis may develop the study at the local site dimension. For the purposes of the current study it is possible to simplify the model of the electrolyser coupled with the RES by using a value of efficiency. The electrolyser is thus modelled as a black box that receives an annual amount of electricity as input and returns the corresponding amount of hydrogen. The conversion is obtained with the product between energy and efficiency. Maintaining the study on the same line, it is obtained the density for the potential production of energy produced in an area.

The electrolyser is the device that permits the conversion from electricity to hydrogen it has to be determined its efficiency. But they exist at least three possible technological alternatives that can be considered: Alkaline electrolysis, Polymeric Electrolyte Membrane (PEM) electrolysis, Solid Oxide Electrolysis Cell (SOEC). They could be analysed other solutions, but this three are the usual reference classes for electrolyser technology. All of them are analysed for what concerns the water electrolysis. Starting from the last one, it is the most innovative but at the same time is currently used only in few applications. It is not considered a suitable solution both for its stage of deployment and for the technical characteristics that make it inappropriate for the application. In fact SOEC technology has a slow dynamic during the operations and that is not appropriate with the coupling with fast changing supply of electricity like RES. Alkaline is a mature technology, already used in industry so with a large reliability. PEMElc is experiencing a rapid grow for pilot projects and industrial deployment, so can be considered as a possible alternative. They share a faster dynamic with compare to SOEC, but PEM is faster than Alkaline one with change of working conditions in the scale of seconds compared to minutes [20] . It is also appreciated for the possibility to directly produce hydrogen at high pressure (70 bar), but at the price of an efficiency decrease. This last characteristic could be considered an advantage in the case study, because could reduce or eliminate the need of device for the pressure increase before the injection in natural gas transmission grid (in the Canadian case, it operates in a range between 14 and 104 bar [29]). According to the typology of RES, the PEM electrolyser could be used for the wind installations while Alkaline slower but more reliable technology could be applied to solar more stable and predictable resource. To find if there is this distinction is motivated by practical reasons they are analysed a series of European projects [36]. Considering the projects about the hydrogen production from RES, there has not been founded any correlation between energy source and electrolyser choice. Moreover the review reports that in the blending projects the two technology are equally deployed, with no distinction according to the size of the application. Even SOEC is involved in few (4) pilot projects, all of them with the methanation purpose for which the technology have interesting advantages.

Both the two electrolysers classes emerge as good options for the case study. From the analysis of their efficiency [20], the data needed for the conversion, it emerges that they are not very different.

	ALK (1 bar)			**PEM (30 bar)**		
MW	1	5	20	1	5	20
kWhe/kg	58	52	51	63	61	58
kg/kWhe	0.0172	0.0192	0.0196	0.0158	0.0164	0.0172

Table 2 Electrolysers efficiency

In the efficiency they are accounted all the operative elements requested to properly run the device (gas purification, water management, cooling system, system control, power supply). The PEM efficiency is decreased by the operational conditions at high level of pressure at the output product. The final choice it has been to derive a mean value from the two technologies efficiencies, in particular using the higher value. It refers to large stacks and it can be considered the real case for large scale applications like the one considered. Up to now there are no big operating plants for large scale green hydrogen production, but hydrogen deploying policies go in this direction. The value obtained are of $54.4\frac{kWhe}{kg_{H_2}}$ or $0.01835\frac{kg_{H_2}}{kWhe}$. For both the technologies it is reported an availability of 98%, thus it has been considered that they are always working while wind and solar plants produce energy.

They have not been considered other kinds of loss that can occurs in the plant, and the potential hydrogen production density has been obtained from the two sources as

$$M_\rho \left[\frac{kg_{H_2}}{km^2}\right] = E_\rho \left[\frac{kWh_e}{km^2}\right] * 0.01835 \left[\frac{kg_{H_2}}{kWh_e}\right]$$

2.3.4 Zone potential hydrogen production and injection analysis

The last step of the analysis concerns the individuation of areas of interest for the hydrogen production and injection in natural gas transmission grid. Data about potential hydrogen production and the description of the natural gas network, provided by the proper layer, has been used to develop a possible solution to the problem. Also if some studies served as inspiration [105][106][60][54], the procedure is mostly an original elaboration. The problem is spatially defined by two elements: the path of the natural gas pipelines and the census division zones. The first one is basically a line and the second a puzzle of polygons. In principle they have nothing in common but the fact to be located over the same territory. In another kind of issue that would have involved other data, they could have been correlated . For example in the case gas production wells location or natural gas consumption data had to be crossed with line trajectory. In that case there is no other a priori correlation but the spatial position. The objective of the study is to find locations which production can directly serve the purpose of injection, so that are located nearby the pipeline itself. The first approach could have been to use the areas that are crossed by the pipelines and then distinguish which one of them would be the most profitable. This approach presents two difficulties.

The first regards the information of the amount of hydrogen requested by the network. As explained in the introduction the hydrogen blending with natural gas in pipelines is nowadays limited and only certain percentages of mixing are allowed. The pipelines doesn't believe as a well that can receive all the potential hydrogen production, but like a consumer that requires a certain one. The second is the error to consider the census division zones as fixed elements to maintain in their entirety. Their role, as stated in problem formulation, has been to provide a common spatial division for the RES elaboration and to capture the local difference at medium scale of detail between the provincial level and the local one. The spatial scansion has no other meaning and use and to use it as the only element of the analysis could lead to this error (figure 29). If the criteria would have been the choice of zones crossed by the transmission pipeline, in that case zones B, C and D would have been select, zone A excluded. Zones C and D are selected only on the base of their being crossed in a minor part of their area, while the majority of their territory develops away from the pipeline (D) or in a completely different area (C). The zone A have a wider, closer area nearby the line, but is excluded because not crossed. It can be argue that the potential of C could be higher of A or B, so that is fair to consider it. The choice of the study is to consider of primary importance the proximity with the line and so the easier access to the source according to the distance criteria. To consider an abundant resource in C as accessible will be an error. The individuation of specific local hubs for the production would be part of a successive analysis.

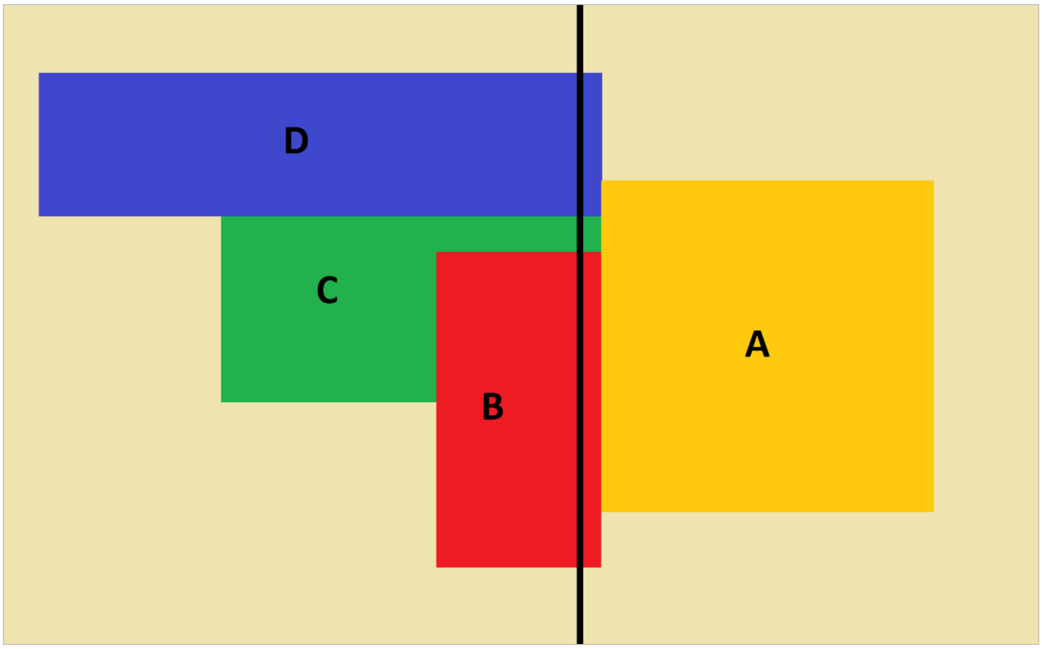


Figure 29 Pipeline and zones analysis. Case 1

The adopted solution has been the following one

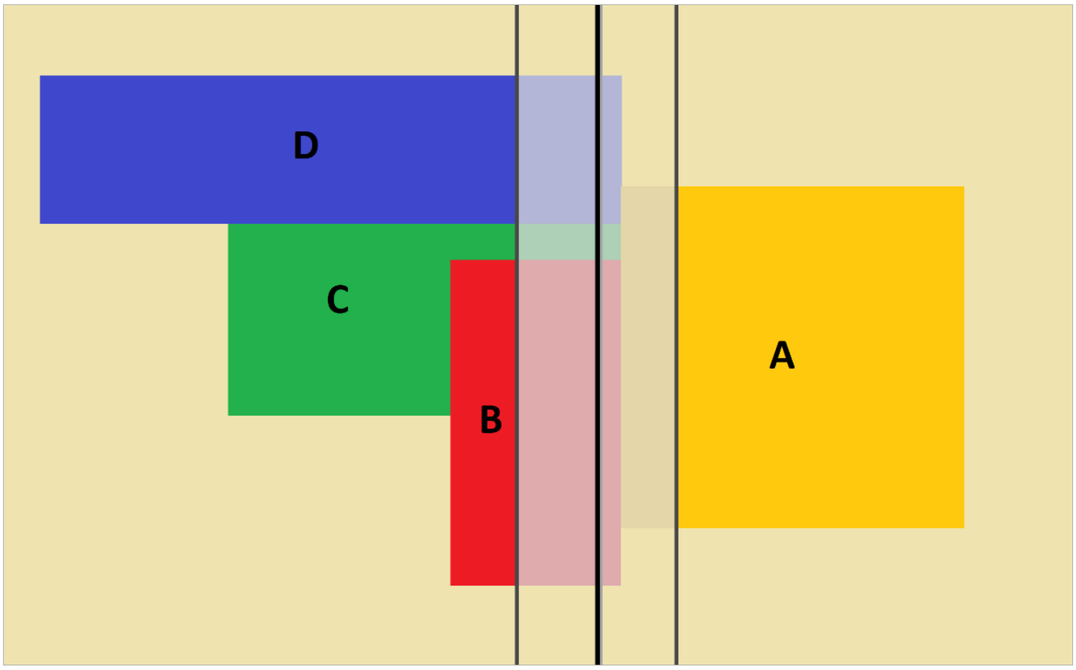


Figure 30 Pipeline and zones analysis. Case 2

where it is defined a new kind of area starting from the pipeline. It is chosen a distance from the pipeline path and identified a bounded area, delimited from both sides of the line at the chosen range. Then from each census division zone it is extracted the area that results from the intersection between buffer area and the zone. The surface value of the intersection multiplied by the potential hydrogen production density of solar or wind source will reinstitute the potential production from this sub-area. The overall hydrogen production is obtained with the sum from all the values. This value is used to estimate the new distance to use. In fact the bounded area expands or recedes according to the demand of hydrogen from the pipeline, until it is satisfied. That is the logic that has been adopted to perform the analysis; they are now explained the method used to realise it.

The delimited area is constructed using the ArcGIS function Buffer, contained in the Proximity toolset within the Analysis toolbox. The function generates buffer polygons at a specified distance of an input feature. It is used the Geodesic Method option to preserve the geodesic and have a better estimations of the distances. The output polygons can maintain the input feature division, resulting in overlapping areas, or be dissolved. The second option has been chosen to generate a unique surface that bounds the pipeline feature. That is the practical result on the software.

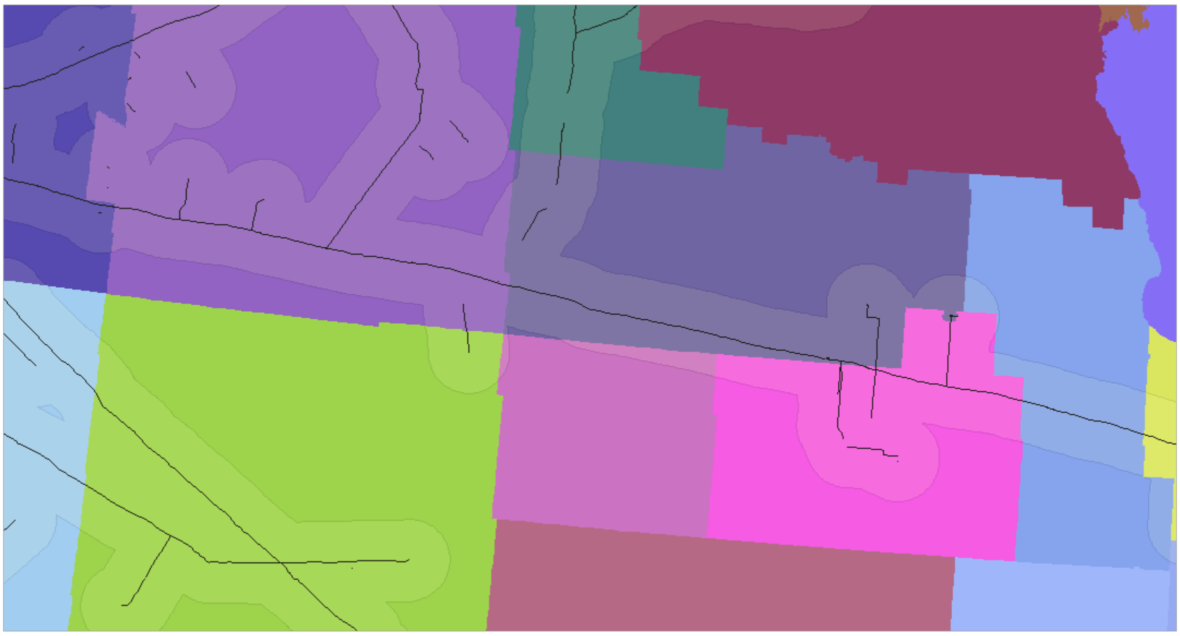


Figure 31 Buffer analysis example from ArcMap 10.6

At the image centre, one area not crossed by pipeline (plum purple) is involved by the buffer analysis. It will be analysed in the result section which has been the impact of these additional elements on the calculation.

To extract the areas from that surface according to the census division zones it is used the Intersect tool, from the Overlay toolset within the Analysis toolbox. The instrument operates an intersection of the input features and produce as output a feature with the overlapping surfaces. In the case study the resulting feature is the pipeline bounding surface divided according the surrounding zones. The layer obtained gets the data characteristics of the input, in this case the fields that characterises every census division zone. Each division is thus identified by a CDUID unique code, that can be associated to a solar and wind hydrogen potential production density. Within the layers table it is possible to create a new field and use the Calculate Field tool to compute the area of each intersection. Once exported into a spreadsheet and performed the association with corresponding potentials data, the hydrogen production is obtained with a simple product.

The procedure is repeated until the overall production meets the pipeline virtual demand from hydrogen. This quantity is based on the annual amount of natural gas transferred through the transmission pipeline and the percentage of hydrogen mixed in the stream. The first data can be interpreted in different ways: it can be both the gas that passes in each section of the line or simply the amount of natural gas delivered by the transmission pipeline. A correct estimation should model the flow of the gas in the different sections, accounting for the fact that a certain percentage could already been met. This consideration would require not only a data on the actual transportation, but also a complex modelling of the steams directions and mixing within the pipes network according to the points of injection. The analysis has been simplified with the assumption that the overall hydrogen production contribute to cover an overall demand, avoiding the problem of the effective delivering that regards another typology of study.

Different sources reports various possible estimations for the data, and it has been used the one provided by CEPA in its 2019 annual report [107] and referring to 2018 data. The source reports the data as the yearly volume of gas "delivered" by the transmission lines of the associated companies, so can be considered as the net quantity that has been transited in the line towards the consume markets. The value is $5.9 * 10^{12}\frac{ft^3}{yr}\,(= 1.67 * 10^{11}\frac{m^3}{yr})$, 54 % used by Canadians and 46 % exported to the US. This differentiation is not accounted in the final value for the calculation because would require a choice of the injection points to distinguish the two amounts. The data is expressed with a volumetric measure while the production potential, via the electrolyser efficiency, is determined in term of mass. While mass in a absolute measure, they are necessary the values of pressure and temperature for the volumetric data reported by CEPA to determine a value of density and operate the conversion. The reference report doesn't report any indication, but it states that data are provided also by provincial and federal regulators. The Canadian Energy Regulator reports [l] a series of conversion factor provided as reference one. There the m^3 are intended as expressed at T=288.15 K and P= 1.01325 bar. The hydrogen density is obtained using the ideal gas law

$$\rho = \frac{P * 10^5}{\frac{8314}{n} * T}$$

with n=2 molar mass of the gas. The result is $\rho = 0{,}08459\,\frac{kg}{m^3}$.

The percentages of hydrogen injection into the transmission pipelines are derived from a NRCan study dated 2017 that analyse the possibilities, limits and problems of this solution in Canada [29]. The analysis reports a general lack of regulation measure on the topic with the exception of local regulators. It bases its consideration on the crossing of technical information from other studies and the status of Canada natural gas system. Limits are reported for both the transport infrastructure and the final use appliance, and three of them has been chosen as significative for the analysis: 2%, 5%, 20%. The lower, 2% , represent the limit within which no or limited action are required for the use of the mixture in the final use appliances. The mid, 5%, is the limit for the transmission grid, establish both by the operators companies regulation and by the energy limit of the mixture. In fact the lower limit for heating value of delivered fuel is 36 MJ/m^3, obtained with a 5% mix of pure hydrogen with the current transported gas. In fact the volumetric heating value of hydrogen ($LHV = 10.8\frac{MJ}{m_n^3}$) with respect of the natural gas ($37.1\ MJ/m_n^3$) determines a decrease of transported energy with respect to volume. The higher limit, 20%, is considered as the maximum sustainable limit for the structural characteristics of the pipeline. The choice is justified by their own meaning, and in particular the last one is a way to estimate the technical achievable potential beyond the current regulations. A possible estimation could have been to estimate the streams to guarantee an amount of energy equal to the current one but with the same transported energy, but that approach is unrealistic because it determines an hypothetical increase of the gas streams for which the infrastructure should be suited. From the chosen percentage applied to the annual volume of transmitted natural gas they are obtained the following values of the hydrogen virtual demand from transmission pipeline.

Hydrogen demand [*10^9 m^3]		
2%	5%	20%
3,34	8,35	33,4

Table 3 Hydrogen virtual demand of transmission pipeline

The exposed procedure is repeated until these three value are met by potential production from wind, solar and both sources together.

3. Results

They are reported the results of the study. First of all they will be displaced significative results for the different steps performed in preparation of the final analysis. The outcomes of this part will be displaced in the form of both numbers and maps, to give a clearer perception of their nature. The final part will be devoted to additional examinations regarding the interpretation of the obtained results in light of both expected one and the used procedure for their calculation. Among the result they will be included some additional calculation related to excluded procedures. They didn't contributed to the final result, but can be interesting comparison to evaluate the achieved results. The various results will be commented in the light of both introduction and methodological consideration and in preparation of conclusions.

3.1 General results

3.1.1 Energy potential production

The initial part of the study doesn't offers interesting results regarding the potential production densities. In fact, as already observed during the exposition of the method to determine them, they are basically transformations of the initial founded values by factors that are constant for all the census division zone. The relevant results has been obtained by the side analysis of the potential energy production obtained all over the country. The result has been obtained with the product of the solar and wind solar energy production and the areas of the respective census division zones. In that way larger areas of the partition benefited from their wider extension, while smaller one with higher potentials became irrelevant. To give a measure of this effect, they are reported the province they belong to the first 10 zones by both the two categories (energy and potential) for both the solar and wind sources and of the surface dimension.

	wind		solar		surface
#	Density [MWh/km2]	Energy [MWh]	Density [MWh/km2]	Energy [MWh]	[km2]
1	Quebec	Nunavut	Saskatchewan	Nunavut	Nunavut
2	Newfoundland and Labrador	Quebec	Saskatchewan	Quebec	Quebec
3	Newfoundland and Labrador	Nunavut	Saskatchewan	Nunavut	Nunavut
4	Newfoundland and Labrador	Nunavut	Saskatchewan	Ontario	Nunavut
5	Newfoundland and Labrador	Ontario	Alberta	Nunavut	Yukon
6	Newfoundland and Labrador	Northwest Territories	Manitoba	Yukon	Ontario
7	Newfoundland and Labrador	Yukon	Saskatchewan	Saskatchewan	Northwest Territories
8	Prince Edward Island	Saskatchewan	Saskatchewan	Northwest Territories	Saskatchewan
9	Prince Edward Island	Manitoba	Manitoba	Manitoba	Manitoba
10	Newfoundland and Labrador	Newfoundland and Labrador	Saskatchewan	Northwest Territories	Northwest Territories

Table 4 RES density and energy ranking comparison

It is clear how in both cases the zones surface size affected the energy transformation, and it is a confirmation that despite being a good way to transform the input data, the census division partition would not been good for the location analysis. For the wind sources (appendix A1 and A2 for the reference maps) all the density potentials areas are located on the east coast, and in mostly in the small provinces of Newfoundland and Labrador (NL) and Prince Edward Island (PEI). Their large presence is related to the fact that a small area with similar characteristics (high mean wind speeds) is divided in many divisions. All these territories are exposed to the Atlantic winds, that determines an interesting source for offshore wind. The energy production maintains only two of these areas, in Quebec (it is the big division in the north of the province) and NL, while all the other are different. In particular they are present the northern territories, with a good wind potentials lowered in the transformation into wind speed average values, but that appears again in energy estimation thanks to their dimension. For the solar resources (reference maps appendix A2 and A3) Saskatchewan first, Manitoba and Alberta too occupy the ranking thanks to the high potential in the terminal part of the Great Plains. They almost completely disappear, with the exception of the two northern division of Saskatchewan and Manitoba, to let appear the territories zones (and Quebec and Ontario bigger divisions too). In that case the effect is purely related to the extension because the local areas of northern territories does not have an energy potential comparable with the southern one.

Before to report the results of the energy potential production, they are compared the outcomes of the available methods considered for both wind and solar production. For the wind case

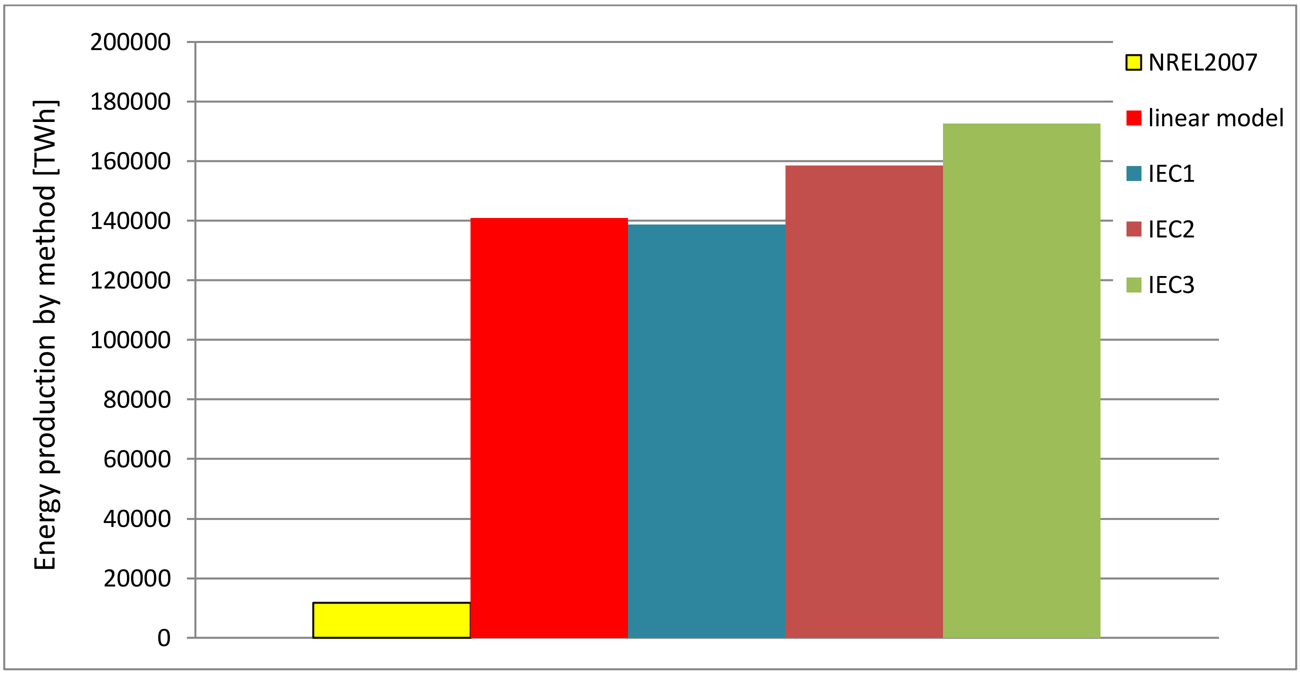


Figure 32 Wind energy results comparison between analysed methods

they are reported the values of the two alternatives method, from NREL2007 study and the GWA based on IEC wind turbines classes. The resources exclusion condition of the first case, that also relate to the resources at 50 m of height, determine a result of one order of magnitude lower than the others. The results of the GWA and used method are on the same scale, with the lower one (IEC1) reporting a lower result. The average capacity factor for this class is around 0.33 while for the chosen method 0.34 (0.38 for IEC2 and 0.41 for IEC3). Despite resulting in a higher linear regression, the outlier values could have a significative influence an determine this result. The outcome obtained can be at least considered in line with the method that does not exclude sources, as chosen for the adopted one. The obtained result of $14.084 * 10^4$ TWh/yr is compared with external references. The 2019-2020 Energy Fact Book [68], based on 2017 data, reports that production of energy from wind has been of 28.8 TWh/yr, the 4.4% of the overall electricity production and 6.5% of production from

RES. The obtained result represent a quantity 3 orders of magnitude higher than current production and more than 216 times higher than the overall electricity production of 652 TWh. Compared with another spatial based estimation [108] of 1380 TWh/yr it still results good, but quite comparable if considering that the study apply land exclusions assumptions. So the result is surely impressive if compared with current data, but acceptable if referred to an estimation of national potential.

For what concerns the solar energy production, it has been already observed that the two methods transforms the mean annual global insolation into the energy potential production density using a similar factor. The result obtained for the energy production confirms this data

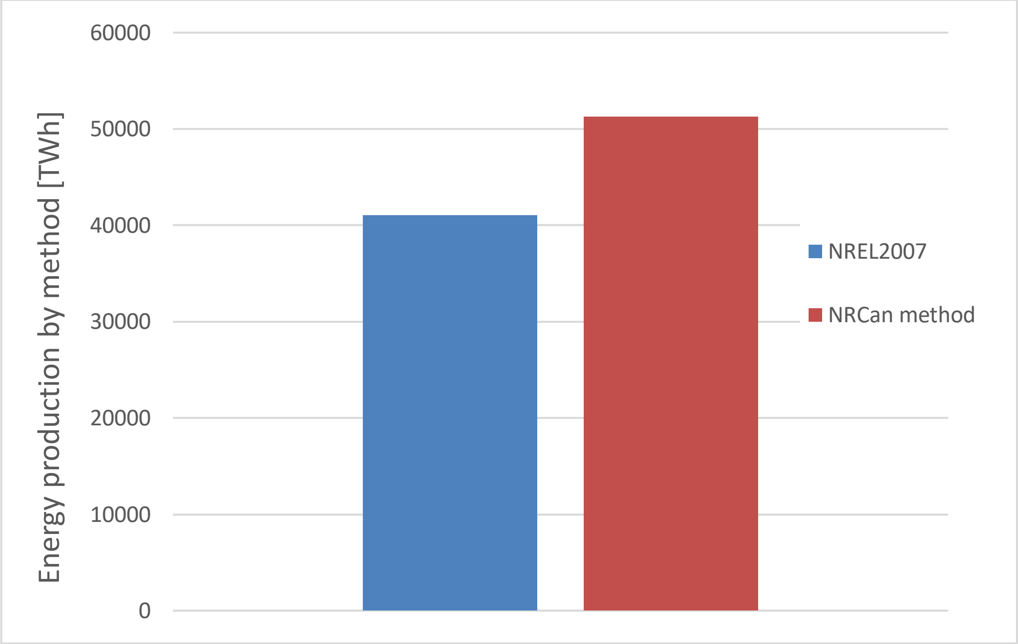


Figure 33 Solar energy results comparison between analysed methods

With a ratio of the two values equal to the two factors already analysed. As observed this data convergence does not offers a complete confirm of the quality of the result, because of the lack of information to justify the NREL2007 approach. At the same time the esteem to the releasing institution is enough to consider acceptable the result of the current study. Comparing with Canadians data the $51.297 * 10^3$ TWh/yr of solar energy production, they appear 4 orders of magnitude higher than 2.9 TWh/yr 2016 solar production (0.44% of total production, 0.66% of RES production) and more than 79 times higher than overall annual production. The result of the other study is 329 TWh/yr, confirming the difference of 2 orders of magnitude already observed. Comparing the two renewables potentials, wind has clearly an higher potential, in particular it is higher by a factor 2.7. The result could be expected for the geographical location of the world and is reflected in the difference between the two energy sources development in the country. They are also much less developed than the first RES and non-RES source of electricity in the country, hydropower. With it 391 TWh/yr (2017) the source covers the 60% of national production and feeds the power exports towards the US, especially in the west coast area. Finally it can be observed how much the territory extension impacts the potential production of energy. Canada is the second bigger country in the world, after Russian

Federation, so it could benefit from an extensive expansion of productive sites. At same time they have to be accounted the detrimental effects on productive sites [109].

3.1.2 Hydrogen potential production

The hydrogen potential production densities directly derive from the energy potentials by the electrolyser efficiency factor. By consequence their spatial distribution is the same of the energy potentials, and the same will be for the results in terms of hydrogen overall production with respect to energy one. Their values are now analysed, starting from the hydrogen potential production density. In the tables below they are reported the average provincial values of the magnitude, for both the solar and wind sources. There are ranked according to the outcomes, and a colour code is used to highlight the best three (green), the worst three (red) and the intermediates values.

#	[kg/km2/yr]	wind	#	[kg/km2/yr]	solar
1	NL	362580	1	Saskatchewan	121394
2	PE Island	345166	2	Manitoba	117347
3	Nunavut	314486	3	Alberta	114097
4	Saskatchewan	308902	4	Ontario	107162
5	Manitoba	299993	5	Quebec	105772
6	Ontario	289753	6	NB	104614
7	NS	275830	7	PE Island	101214
8	Quebec	268767	8	NS	98105
9	Alberta	268325	9	NWT	94660
10	NB	256375	10	BC	93135
11	NWT	237134	11	Nunavut	92797
12	Yukon	180349	12	NL	87319
13	BC	173275	13	Yukon	87135
National average		275457	National average		101904

Table 5 Hydrogen potential production density by source

They are also displayed the map for the wind (figure 34) and solar (figure 35) production densities. Starting from the wind data, the 3 best areas are Newfoundland and Labrador (NL), Prince Eduard Island (PE Island) and Nunavut. This last one territory already appeared in the ranking for best energy productive areas, thus its potential is related not only to its extension. The area of mid potential located in the central plains remains in the middle part while the hot spot on the British Columbia (BC) mountains are lowered by the correspondent effects in the valleys, and the province rank last one. The solar results too confirms the previsions, with the three central provinces being at the top and two of the three northern territories at the lower level. Northwest Territories (NWT) benefit of the relatively good potential around Hudson Bay, ranking higher than BC where some of the national lowest values in the west coast determine a bad average value. It can be noticed that the difference between the ranking top and down values is wider in the wind case than in the solar one. In particular their ratio is 2.1 in the first case, 1.4 in the second, so instead of being solar source the one that change more across the country, it is the wind one. A comparison of the data can be done with the NREL2007 results. This study reports national values for US equal to 94933 kg/km^2 for wind and 265028 kg/km^2 for solar sources. The values are at a comparable scale with respect to the Canadians one, with the wind value lowered by strong exclusions and solar one that can take advantage of the larger source availability.

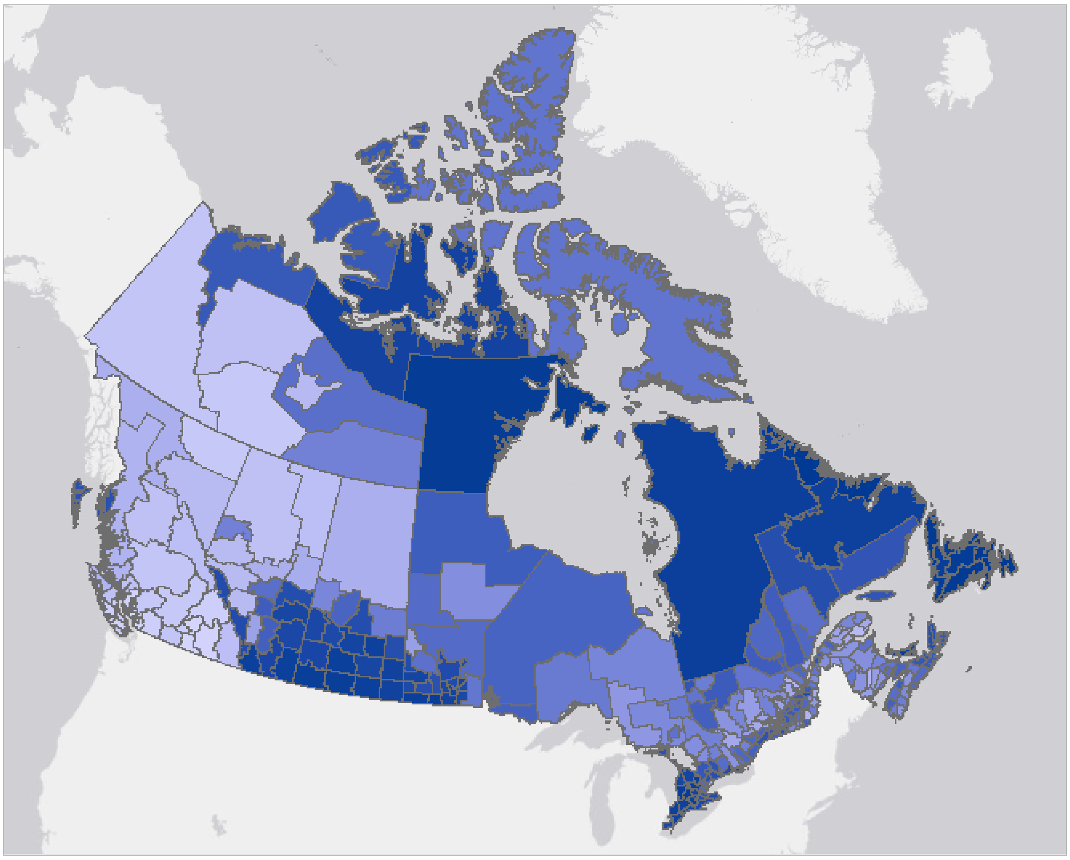


Figure 34 Hydrogen production density from wind sources

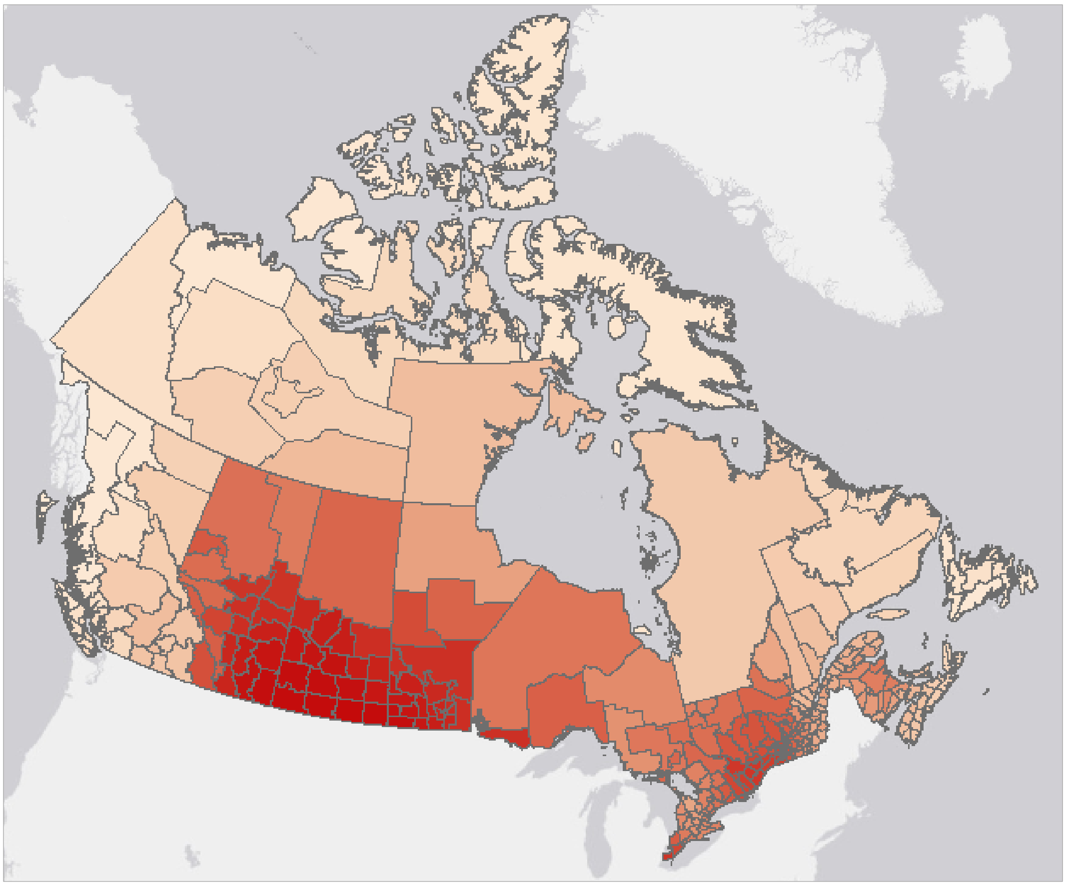


Figure 35 Hydrogen production density from solar sources

Before to proceed with the analysis of the overall hydrogen production, they are examined the data regarding the involved territories surfaces. It has been already pointed out how much the extension of the different divisions play an important role. During the procedure exposition it has been explained that the values of single census division zones has been calculated using the Field Calculation corresponding function. To evaluate the accuracy of that one calculation, the following table has been constructed.

#	[km^2]	Official	%	Calculated	diff%	%	div. Num.
1	Nunavut	2093190	21.0	2010566	3.9	21.0	3
2	Quebec	1542056	15.4	1476349	4.3	15.5	98
3	N W T	1346106	13.5	1277218	5.1	13.4	6
4	Ontario	1076395	10.8	980244	8.9	10.3	49
5	B C	944735	9.5	917732	2.9	9.6	29
6	Alberta	661848	6.6	639936	3.3	6.7	19
7	Saskatchewan	651036	6.5	632215	2.9	6.6	18
8	Manitoba	647797	6.5	627594	3.1	6.6	23
9	Yukon	482443	4.8	455687	5.5	4.8	1
10	N L	405212	4.1	397597	1.9	4.2	11
11	N B	72908	0.7	74525	-2.2	0.8	15
12	N S	55284	0.6	57534	-4.1	0.6	18
13	P E Island	5660	0.1	6023	-6.4	0.1	3
Total		9,984,670	100	9,553,222	4.3	100	293

Table 6 Census division zones surfaces analysis

The Provinces and Territories are reported ranked by their values, but two categories of value are reported: official and calculated. The first one represents the official, the second one the result of the summary of the single census division zones. It has to be observed that official calculation define surfaces as the areas within land borders, thus comprehends also the surfaces of internal waters (lakes, rivers). The calculated one accounts for all the area within census division zones, because the function define the surface within the borders. It ca be observed in the field diff% the relative difference, with respect to the official value, for each Province or Territory. Some of them are quite impressive, like almost 9% for Ontario, 5.5% of Yukon, 5% of Northwest Territories or -6.4% for Prince Eduard Island. In general none of them are exactly estimated, despite the use of geodesic option for calculation. They could have been used tables of the surfaces estimated by Statistics Canada, but the definition of potential has been performed by the software on these areas, within the Zonal Statistics as Tables (ZST) functionality. At same time the central analysis of the study is performed using completely different and handmade surfaces, so not involving these potentially more accurate values. It is important to observe that the proportions of the areas as been maintained, as demonstrated by the two "%" fields. The relative dimensions has been largely respected, and so the relative impact of the different areas. The last field reports the number of census divisions for each Province and Territory. The already quoted and discussed difference of zones areas can be detected from the first two classified in the surface ranking: the first one Nunavut has 3 zones, the second Quebec 98 (the higher number), and they represent respectively 21% and 15.5% of national territory. The analysis can proceed with the values of overall hydrogen production, displayed in the following maps for the solar and wind source production. The colour ramp represents the increase in the zonal production.

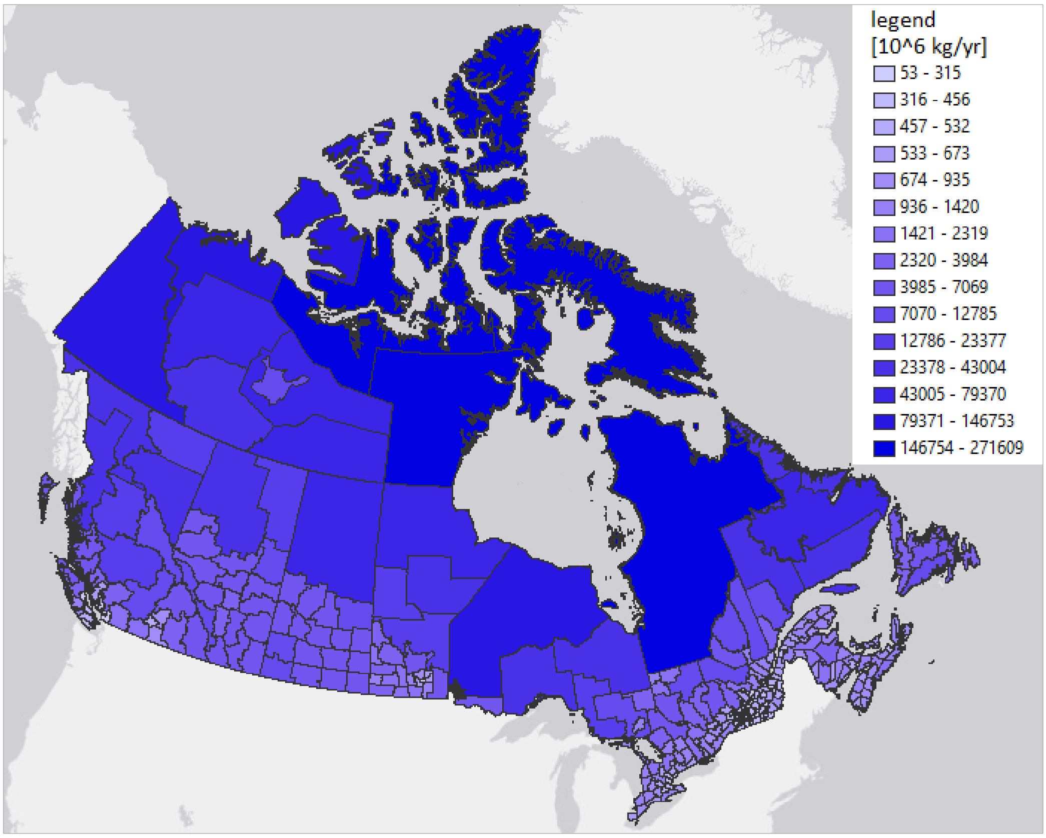


Figure 36 Production of hydrogen from wind source by zone

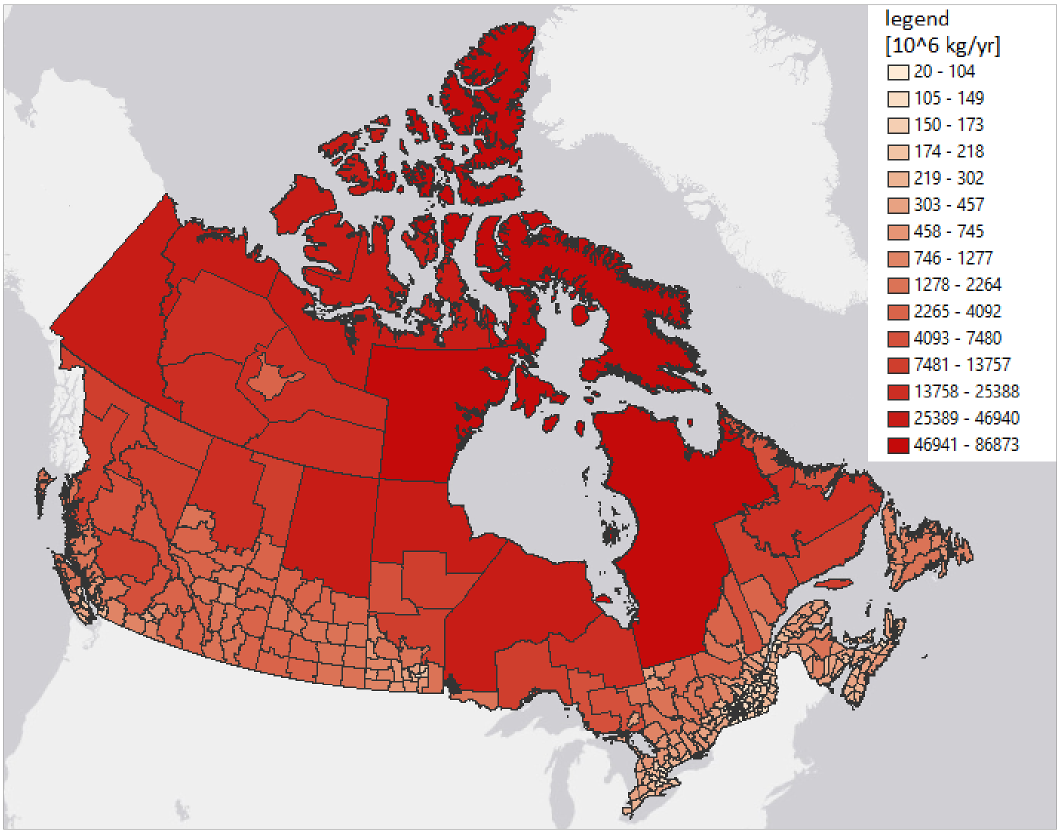


Figure 37 Production of hydrogen from solar source by zone

The colour ramp has been constructed using the same distribution (geometric progression between maximum and minimum values), thus it can be noticed how the distribution of the values for each zone is almost the same. The values in the smaller divisions are as expected the lower one, as an effect of the inhomogeneous spatial partition of census division. An example of this displacement occurs within Quebec province, with one of the highest values on its huge north division and some of the lowest one in the southern divisions, so tiny that are not clearly distinguishable at country scale. To have a clearer idea of the territorial distribution of the potential production, the data are summarized in the following tables, that use the same structure of the one used for the description of the production density. The data are summed up adding the data of all the zones by province. It is also calculate the % of total production achieved by each federal division.

#	[10^10 * kg/yr]	wind	%
1	Nunavut	60.8	23.5
2	Quebec	45.3	17.5
3	N W T	31.3	12.1
4	Ontario	26.6	10.3
5	B C	18.5	7.2
6	Saskatchewan	17.4	6.7
7	Manitoba	17.4	6.7
8	Alberta	15.4	6.0
9	N L	13.7	5.3
10	Yukon	8.2	3.2
11	N B	1.9	0.7
12	N S	1.6	0.6
13	PE Island	0.2	0.1
National total		258.4	100

#	[10^10 * kg/yr]	solar	%
1	Nunavut	18.3	19.4
2	Quebec	14.8	15.7
3	N W T	11.8	12.6
4	Ontario	10.5	11.1
5	B C	8.5	9.0
6	Saskatchewan	7.3	7.7
7	Alberta	7.1	7.5
8	Manitoba	6.9	7.3
9	Yukon	4.0	4.2
10	N L	3.6	3.9
11	N B	0.8	0.8
12	N S	0.6	0.6
13	PE Island	0.1	0.1
National total		94.1	100

Table 7 Potential hydrogen production by source

The two rankings are almost equal with the sole exception of the inversion between Alberta-Manitoba and NL-Yukon positions. The first 5 position and the last 3 are the same of the surfaces ranking, with the first case maintained by spaces dimensions and the second one by small extensions. In the intermediate positions the differences in the hydrogen production density played a small role, but nothing really significative. Even the proportions expressed by the percentages remain almost the same, the definitive proof of the spatial impact on a national scale calculation. It is more interesting to confront the total value for the two RES with other one. The result in the NREL2007 study are $273.36*10^6$ kg/yr for wind and $717.49*10^6$ kg/yr for solar production. They are four and three orders of magnitude lower than the values obtained from the study. While wind energy resources could be comparable, the solar one are for sure higher in the US, in particular in its southern territories. The overall surfaces are almost equal (9,984,670 km^2 for Canada and 8,080,464 km^2 for contiguous US), thus the mainly difference and cause of US lower values is the adoption of land exclusion. As observed for the study used as comparison for energy sources, the effect of this additional element is quite important to determine a more accurate estimation of the potentials.

An additional and interesting comparison is the one with Canadians energy production and consumption. While RES energy potentials have been compared with national electricity generation, the term of comparison for hydrogen are fossil fuels, and in particular natural gas. This last one is the source that, in the intentions of the study, will compete with hydrogen in transmission network and thus, potentially, in final consumption. As considered in the introduction, natural gas can be either be separated from the stream at distribution level to reproduce an high purity gas, or remain mixed and be used for the current purposes for which natural gas is used today. That means largely combustion, for heat or power generation. This second option is considered the way to compare the two sources: the projects that are implementing hydrogen mixing foresee in the short term this typology of use for the mixture, and the analysis of separation and fuel cells reconversion routes would require a definition by technology and final use.

So to compare the two quantities they are used their volumetric Lower Heating Values (LHV) at the reference temperature and pressure conditions, equal to 35.63 MJ/m^3 for natural gas and 10.37 MJ/m^3 for hydrogen. With the conversion of mass based value in to volume one (ρ =0.0846 kg/m^3) , and the energy conversion, they are obtained the values for wind and solar hydrogen: 3.17*10^{14} MJ/yr and 1.15*10^{14} MJ/yr. Canada currently produce 1.88*10^{11} m^3/yr of natural gas [68], mostly in Alberta (69%) and British Columbia (29%), equivalent to 6.70*10^{12} MJ/yr. The potential hydrogen production have an energy content 47 and 17 times higher than the current natural gas production, considered one of the pillars of Canadian energy system. The 46% of this production is exported to US, with the pipeline paths already examined, and covers the 9% of the American consumption. That result in an export of 0.86*10^{11} m^3/yr (3.1*10^{12} MJ/yr) toward a market of 9.6 10^{11} m^3/yr (34.44 MJ/yr). The potential production it is not only energetically bigger than the exports, but of the overall export market.

The final confrontations can be performed with the values of the Canadian natural gas network, both the overall and the different percentage of injection and mixing.

% injection	[10^10 m3/yr]	wind	solar
100% vol	16.7	183	67
2% vol	0.334	9147	3331
5% vol	0.835	3659	1333
20% vol	3.34	915	333

Table 8 Natural gas capacities comparison with overall production by source

It is clear how the production overcomes even the value of the current transported natural gas. The infrastructure surely has not the capacity to sustain these quantities, and they are distributed in areas where the network does not extent. The comparison has been performed as a preliminary step, to verify the possibility to cover the injection data using the available potential sources.

3.2 Buffer analysis

The final part of the study has been the calculation to determine the areas of major interest, using the buffer functionality as a way to explore the surrounding of the pipeline path to explore the potentials of the zones. In this chapter they will be first of all reported the results; than they will be discussed different numerical aspects of the results to understand the way the method determined the outcomes.

In the section with the method explanation they has not been exposed all the iterations done to get the final result. The first distance used for the analysis has been 1 km, but the result already resulted in productions higher than the requested for all the three percentages of injection in the pipelines. It has been lowered the value, and the following results has been obtained. The table below is the one used to analyse the percentage of injection virtual demand, covered by the production of the two sources within the area delimited by the buffer distance. Red values are the one below the required one, the green one are above the demand.

buffer distance	**10 m**			**0.1 km**			**0.3 km**			**0.5 km**		
injection %	**2%**	**5%**	**20%**	**2%**	**5%**	**20%**	**2%**	**5%**	**20%**	**2%**	**5%**	**20%**
wind	0.56	0.22	0.06	5.59	2.24	0.56	16.71	6.68	1.67	27.77	11.11	2.78
solar	0.24	0.09	0.02	2.35	0.94	0.23	7.02	2.81	0.70	11.68	4.67	1.17

Table 9 Buffer analysis iteration progresses extimation

The lower value used has been 10 m. It is of course not a realistic one, but once 0.1 km (100 m) has been reached, to perform a detailed analysis with lower values has been considered useless. That consideration rose both by the specifics of software precision at that level of detail, and the practical applications of that kind of result. At 10 m no demand is satisfied, but at 100 m the 2% is already covered. At 0.3 km (300 m) 5% too is obtained and 20%, already produced by wind, has been almost obtained by solar. At 0.5 km (500 m) they are all green. The results obtained does not report the precise distances at which the fraction can be obtained, but that would be not impossible, but useless from the point of view of the result meaning. The limits of software detail has been already exposed, and another reason relate to the detail of the data adopted. They are the outcomes of methods ([81], [83]) that reconstruct the distribution of resources starting from few data gathered across the territory. Their strength is the possibility to derive informations for large spaces, but that is at the same time their limit. In addition to that the method used dilute the level of detail of initial data to perform a more agile analysis. To go more in deep with the distance analysis would have mean to force the possible consistent level of detail, getting data with no additional informations that the one achieved. Despite the result, the analysis has been performed up to 13 km of distance, with other three intermediate values (3 km, 5 km and 10 km). The purpose of the study was not only to explore the resources, already proved largely available in the surrounding of the pipeline network, but also to have more data for an eventual successive analysis of the method. The tables with complete results for energy and hydrogen production for all the distances will be reported in the appendix B.

They were not expected these results for the buffer distance. The Canadian natural gas transmission lines are around 115000 km long [84], but it is difficult to quantify the impact of a surrounding area dispersed all over the territory. The values of areas obtained with the intersection method are reported in the table below (table 10), compared with overall calculated area in term of per thousand fraction. The areas have a small impact in the national scale, but the larger outcomes explored arrive at 5.5%

and 7% of Canadian territory. They are quite big, but the required hydrogen demand is already covered by a surface that is around the 0.2% (between 0.3 and 0.5 km) of national land surface. It is difficult to have a clear idea of what kind of impact that would represent in term of soil occupation, but this aspect is not considered in the current study.

distance [km]	[km2]	‰
0.01	596	0.1
0.1	5946	0.6
0.3	17774	1.9
0.5	29592	3.1
1	58820	6.2
3	172775	18.1
5	280517	29.4
10	525196	55.0
13	655005	68.6

Table 10 Buffer analysis areas

These areas are not equally distributed across the country. In table below they are reported the overall values of areas defined by the buffer analysis at each step, in particular in the more meaningful for what concerns the coverage of requested quantities.

Areas	0.01		0.1		0.3		0.5	
	[km2]	%	[km2]	%	[km2]	%	[km2]	%
Alberta	241.19	40.47	2412.02	40.57	7204.16	40.53	11955.57	40.46
Saskatchewan	116.03	19.47	1161.38	19.53	3481.01	19.58	5801.63	19.63
Ontario	105.20	17.65	1033.25	17.38	3063.41	17.23	5076.19	17.18
B C	84.50	14.18	847.39	14.25	2548.26	14.34	4252.96	14.39
Manitoba	22.42	3.76	224.57	3.78	672.73	3.78	1119.19	3.79
Quebec	15.30	2.57	153.52	2.58	461.86	2.60	771.80	2.61
NW T	11.06	1.86	110.93	1.87	333.85	1.88	557.90	1.89
N L	0.10	0.02	1.03	0.02	3.44	0.02	6.25	0.02
N B	0.10	0.02	1.03	0.02	3.28	0.02	5.79	0.02
Nunavut	0.09	0.02	0.93	0.02	2.92	0.02	5.00	0.02
N S	0.00	0.00	0.00	0.00	0.03	0.00	0.21	0.00

Table 11 Distribution of surfaces involved in the spatial analysis

The percentages of areas remain almost constants in the different steps. This effect can be related to the fact that the analysis evolves by enlarging the areas everywhere by the same factors, thus the proportion have to remain almost constant. The only differences are related to the effects of overlapping that occur with adjacent sections of the line, because in this case there is no surface increase despite the range enlargement. The distribution of surface across Provinces and Territories is obviously related to the structure of the Canadian natural gas transmission lines, already analysed in the data acquisition section. In particular it is relevant the 10 m case study, with a buffer area almost corresponding to the line itself. More than the majority of the lines are located within Alberta and Saskatchewan. Here it is located a dense grid of transmission pipelines for the presence of the almost totality of Canadians natural gas extraction fields. The lines serves as gathering network from the feeding lines, and are the starting points for the transmission to east or south. In Quebec and Ontario the transmission pipelines deliver natural gas to the densely inhabited and industrialized areas. Analysing the lower values, Nova Scotia value for lower distances is 0, and it emerges with a small surface only from the 300 m distance. That is quite a strange behaviour, and it is related to the location of a long section of the pipeline (in particular a Mixed typology one) within a river. That could be effectively a pipeline section or an error in the database. The pipeline data for NL, NWT and Nunavut are represented by small lines, and like in the case of NS it is not clear if they are errors or effective sections of transmissions pipelines. They area contribution is almost zero, and that will determine their impact on final results.

3.2.1 Wind hydrogen

The objective of the study has been to find locations of interest for the hydrogen production and injection in the natural gas transmission lines. The more important results obtained are the one regarding the spatial distribution of productions that more contribute to satisfy the estimated virtual demand. They are analysed these value for both the RES. Starting from the wind resources, the first analysis it is performed at the aggregation level of Provinces and Territories, summing the values that has been obtained in the zones involved within them.

Wind	**0.01**		**0.1**		**0.3**		**0.5**	
	[kg/yr]	%	[kg/yr]	%	[kg/yr]	%	[kg/yr]	%
Alberta	6.26E+07	39.51	6.26E+08	39.62	1.87E+09	39.61	3.10E+09	39.54
Saskatchewan	3.68E+07	23.21	3.68E+08	23.29	1.10E+09	23.35	1.84E+09	23.41
Ontario	2.95E+07	18.65	2.90E+08	18.36	8.59E+08	18.20	1.42E+09	18.14
B C	1.63E+07	10.32	1.64E+08	10.37	4.92E+08	10.43	8.22E+08	10.47
Manitoba	6.82E+06	4.31	6.83E+07	4.32	2.05E+08	4.33	3.40E+08	4.34
Quebec	4.19E+06	2.65	4.21E+07	2.66	1.27E+08	2.68	2.11E+08	2.69
NW T	2.07E+06	1.31	2.08E+07	1.31	6.25E+07	1.32	1.04E+08	1.33
N L	3.22E+04	0.02	3.42E+05	0.02	1.15E+06	0.02	2.10E+06	0.03
Nunavut	2.90E+04	0.02	2.98E+05	0.02	9.39E+05	0.02	1.61E+06	0.02
N B	2.69E+04	0.02	2.78E+05	0.02	8.86E+05	0.02	1.56E+06	0.02
N S	0.00E+00	0.00	0.00E+00	0.00	9.23E+03	0.00	6.03E+04	0.00

Table 12 Provincial aggregation for hydrogen production from wind resources for different value of buffer distance

The outcomes are ranked from the point of view of growing production value in the 0.5 km field, considered the most significative both because covers all the production and it is the more significative from a practical point of view. The same colour scheme already adopted is used to highlight the provinces that could more profitable for the application. To give a better idea of the impact of each province production, it is reported the percentage over the overall production at each buffer distance. The first province is Alberta, that covers almost 40% of the production at every distance. Saskatchewan follows with more than 23% of production, thus the first two provinces can derive from their zones around 63% of overall production. They follow Ontario, with a mean 18.5% of production, and British Columbia with more than 10%. The first four provinces represents more than 91% of the production at every distance; they are ideally able to cover all the virtual demand for hydrogen injection and even to produce bigger quantities. Nunavut ranks among within the red field, while it was one in the top three of the hydrogen production density and the first one for both wind and solar potential hydrogen production. A similar case occurs to Newfoundland and Labrador (N L), first in the wind potential production density rank. The absence of infrastructure make their sources unavailable for mixing purposes. Prince Edward Island (PEI) and Yukon do not appear in the list because no transmission pipelines cross them. The case of Yukon would not be of interest in any case, with its low potential resources. PEI could have offered interesting wind resources, but with its small territory not a big production could have been achieved. To better confront the impact of best performing provinces, it is compared their potential production for the different distances.

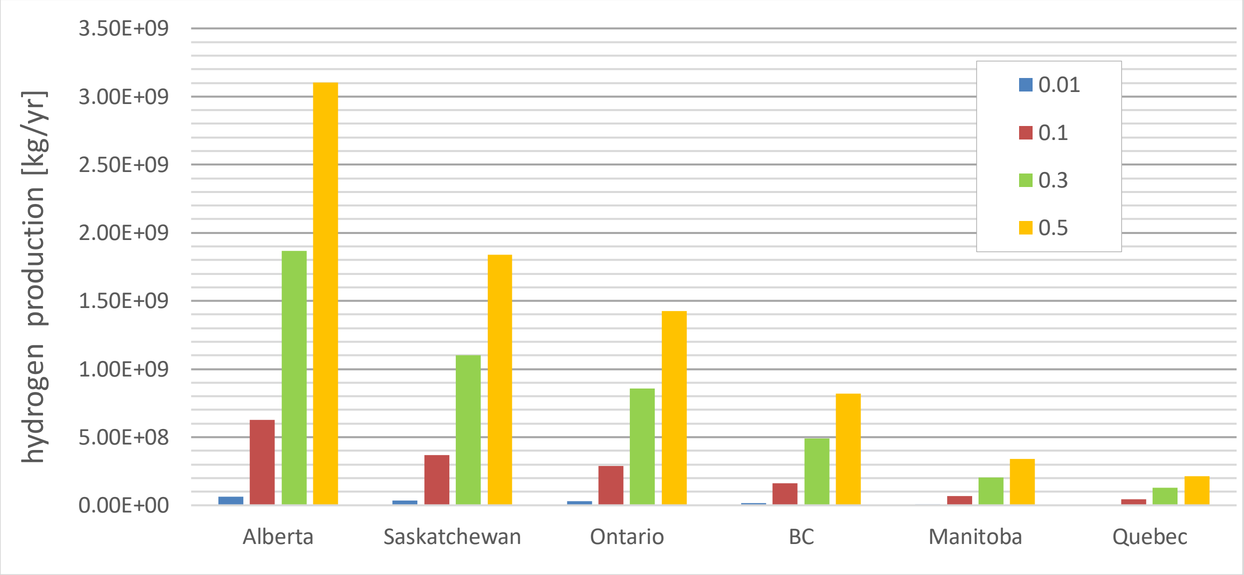


Figure 38 Top 6 province for hydrogen production from wind resources by buffer distances

These provinces together represents around 98.6% of the total potential production. Alberta stands out over the others provinces, and the distance seem to increase with the increasing buffer range. With Saskatchewan, British Columbia (BC) and Manitoba they let emerge the west part of the country as the more interesting one. The aggregative analysis at provincial level let emerged some macro productive areas. With a lower level of analysis it should be possible to understand if it is only an extensive effect or if there are areas with higher potential, suitable for production from a technical and economical point of view.

For the map displaying production areas (figure 39) they are used the data of the buffer analysis at 500 m for the reasons already exposed. The colour scale indicates the value of the hydrogen production, for each zone, derived from the buffer analysis. The darker the colour, the higher the value, while white areas have no production because crossed by no pipelines. As observed by results, the majority of high value areas are located in the west of the country, in particular in Alberta and Saskatchewan. Considering Manitoba as a spatial watershed of the territory, four of the top 6 production areas are located in the west. Alberta particularly benefits from the presence of the infrastructure, and its entire territory is contributes to the potential hydrogen production. Something similar occurs in Saskatchewan, where only the big north division is not involved. In Quebec and Ontario the potentials zones develops on an ideal line from the Great Lakes along the San Lawrence River, following the path of transmission lines. The contribution of Quebec comes almost totally from small census divisions along this path, while its north remains unexplored by the analysis.

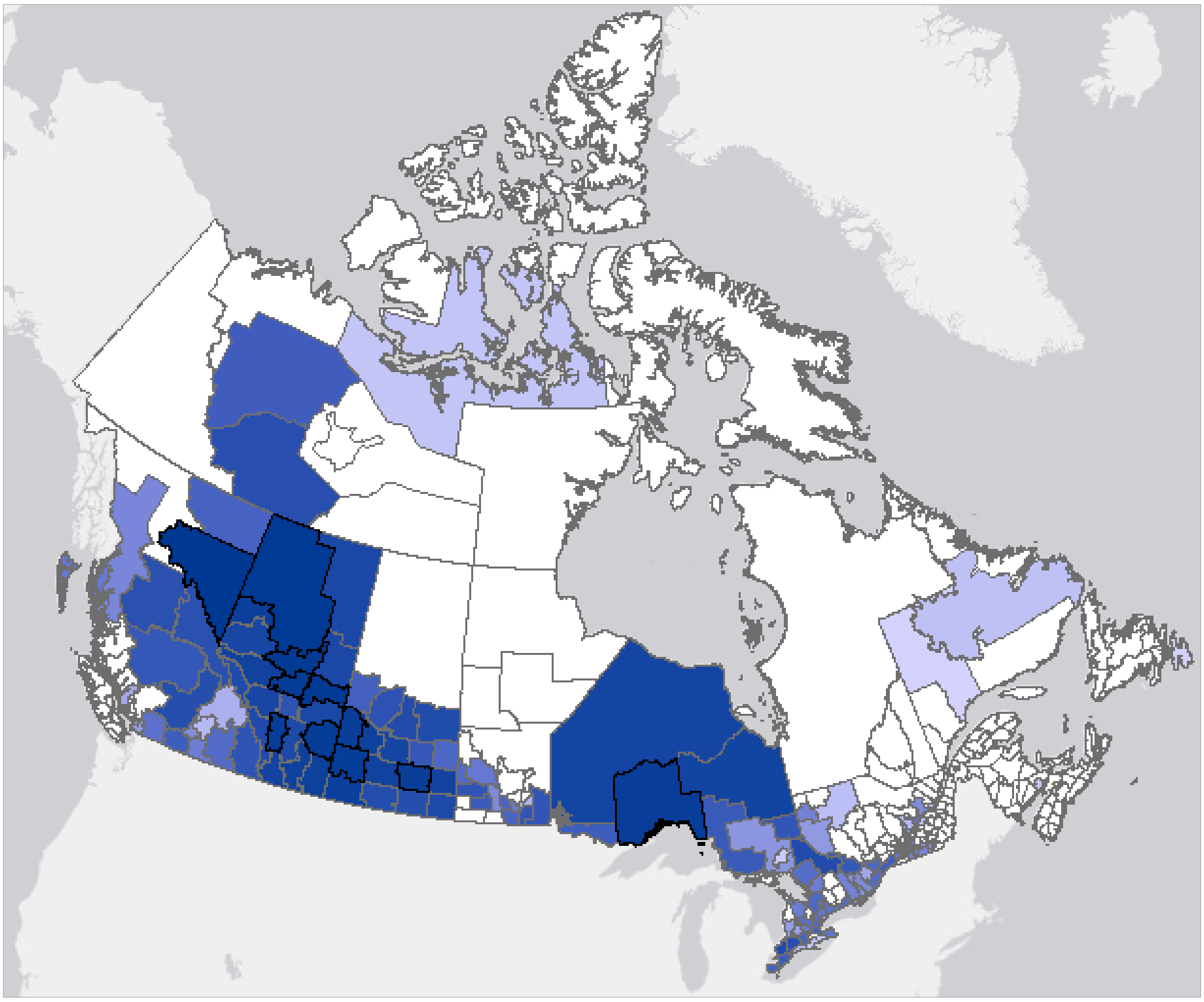


Figure 39 Distribution of zones for hydrogen production from wind resources according to 500 m buffer analysis

A different thing occurs to Ontario, where in addition to the Lakes area it is involved also the west part of the Province. Here the west-to-east natural gas transmission is granted by the TransCanada line, that in its path cross the south part of Manitoba. To focus the analysis on the characteristics of the best 11 performing zones (in the map the one with the black borders), the table 13 displays their values for hydrogen production, surface at 500 m buffer analysis and wind potential production density. It is also reported for each field the rank of the zone within the 144 divisions involved in the 500m calculation. The best productive area is the one located in north British Columbia, but Alberta follows with 5 of its 6 ranked zones. Saskatchewan is represented by 3 zones and Ontario by its most productive one, at north of Lake Superior. For localisation purposes they are reported the names of the census divisions. Both for Alberta and Saskatchewan it is used a name system that associate the partition to a number. That explain the repetition of one name, and the specific case is identify by the Province and the CDUID code. Their overall production could potentially cover the 33% of the total production at 500 m. That is a quite impressive value, but the zones of Alberta represents the 49% of their Province production at the same range analysis, thus it can be explained. This values are product of the zone intersection area and the potential of the zone. To analyse these values means to understand if the result is more related to the extensive or intensive potential. The areas of all the involved zones are the among the biggest obtained with the buffer and intersection proceed, also if the previous ranking order is not maintained. They sum up the 34% of all areas, largely related to the dense transmission network in Alberta. The analysis of the production density depict a different picture. The best performing are the zone located in the southern part of Saskatchewan (28th and 33rd) and Alberta (35th and 36th), while 6 of the others are below the median value. That is not a surprise: the BC wind density was the last one and Alberta ranked 9th. Despite that, the average value of the production density is completely in line with the other zones average value and even with the national one, that was 275457 kg/km2/yr.

Province	Census division	Production [kg/yr]		Area [km2]		Density [kg/km2]	
British Columbia	Peace River	1	333227525	2	1519	122	219348
Alberta	Division No. 17	2	308902444	1	1542	130	200290
Alberta	Division No. 10	3	286910943	4	944	47	303956
Alberta	Division No. 13	4	250660519	3	1044	119	240164
Alberta	Division No. 4	5	250436675	6	794	36	315267
Alberta	Division No. 11	6	249552485	5	924	81	269950
Saskatchewan	Division No. 8	7	204405078	10	640	33	319162
Ontario	Thunder Bay	8	189110736	7	716	91	264168
Alberta	Division No. 6	9	176506449	8	715	112	246903
Saskatchewan	Division No. 13	10	175808289	14	556	35	316177
Saskatchewan	Division No. 6	11	166870718	16	520	28	320666
WIND		total	2.59E+09	total	9916	average	274186
		% 500 m	33	% 500 m	34	% 500 m	101

Table 13 Best 11 zones for wind hydrogen production at 500m buffer analysis

The examination confirms that the surface value is the driving factor for the method, as already noticed for the analysis of the values aggregated on provincial level. The divisions are quite big: Peace River places 20th in overall surface ranking, Alberta No.17 places 15th , the smallest one is Alberta No.6 that is 97th in a total of 293 divisions. At the same time the method objective was to capture the combination of surface and potential with the availability of an existing infrastructure. The density data is not the optimal one, but as observed is in line with the Canadian mean one. The displacement and discussion of results has been done only of the 500m for the reasons already reported. Another element that makes the analysis at other buffer distances useless for a detailed examination of the zones is the observed impact of the areas itself. In fact since surfaces ratios among provinces remains constant and much more wider than the density values, it can be deduced that the impact of zones remains almost the same for the other distances. It can be also foreseen how the solar production too will result in similar distribution, with few variations in ranking due to density values. For what concerns wind potential hydrogen production for injection in natural gas transmission network, from this study it emerges that best areas for possible are the central and southern zones of Alberta and Saskatchewan. They combine both the presence of an infrastructure and a good wind source availability. The region in the north west among BC and Alberta offers a large territory and the available line, but the production density is very low as a result of poor wind conditions. West Ontario too could offer good opportunities, but it has to be estimated the profitability of their development for this purpose.

3.2.2 Solar hydrogen

Using the same schematics, they are reported the data concerning the analysis for solar sources. As observed in the initial iterations table, the solar source result lower than the wind one and needed a higher buffer area to satisfy the injection demand. The ranking on the base of 500 m buffer distance remain the same than the one observed for the wind sources, a confirmation of the role of pipeline shape in the determining the distribution of the production by province.

Solar	0.01		0.1		0.3		0.5	
	[kg/yr]	%	[kg/yr]	%	[kg/yr]	%	[kg/yr]	%
Alberta	2.73E+07	41.08	2.73E+08	41.17	8.16E+08	41.14	1.35E+09	41.06
Saskatchewan	1.42E+07	21.42	1.43E+08	21.49	4.27E+08	21.54	7.12E+08	21.59
Ontario	1.13E+07	16.97	1.11E+08	16.71	3.29E+08	16.57	5.45E+08	16.52
B C	8.27E+06	12.43	8.29E+07	12.49	2.49E+08	12.57	4.16E+08	12.61
Manitoba	2.68E+06	4.02	2.68E+07	4.04	8.03E+07	4.05	1.34E+08	4.05
Quebec	1.65E+06	2.48	1.65E+07	2.49	4.97E+07	2.51	8.31E+07	2.52
NW T	1.04E+06	1.56	1.04E+07	1.57	3.14E+07	1.58	5.25E+07	1.59
N B	1.02E+04	0.02	1.06E+05	0.02	3.38E+05	0.02	5.96E+05	0.02
N L	9.14E+03	0.01	9.64E+04	0.01	3.19E+05	0.02	5.80E+05	0.02
Nunavut	8.26E+03	0.01	8.50E+04	0.01	2.68E+05	0.01	4.59E+05	0.01
N S	0.00E+00	0.00	0.00E+00	0.00	2.99E+03	0.00	1.95E+04	0.00

Table 14 Provincial aggregation for hydrogen production from solar resources for different value of buffer distance

Looking deeply at data, the share of Alberta production rises to 41 %, Saskatchewan follows with 21.5 % and third comes Ontario with more than 16.5 %. The data of the first two contributors lowers to more than 62.5%, and the first four value sum up more than 89.7 % of production at 500 m. British Columbia becomes more relevant in its contribution while all the others decrease their one.; its value of solar potential production density ranked better than the wind one. Other territories give a low contribution or are excluded for the same reasons related to the pipeline data already explained.

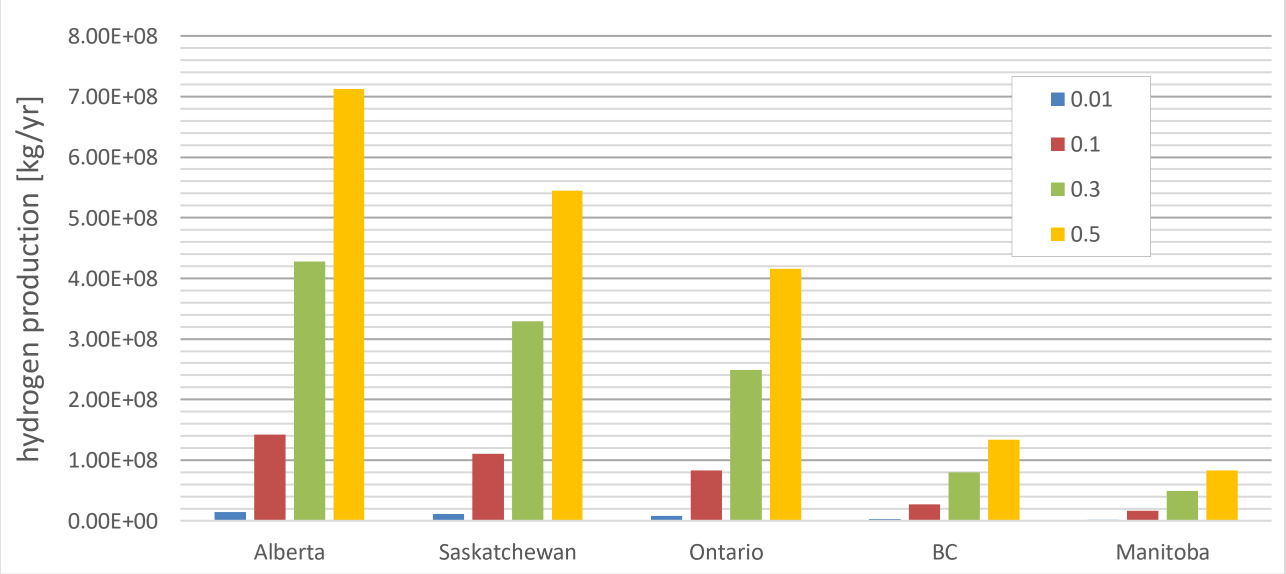


Figure 40 Top 6 province for hydrogen production from solar resources by buffer distances

The first 6 productive provinces are the same (figure 41), but the upper production values behalf with respect to the wind one. It also differs the absolute quantity of their difference: if for wind it was of 10^9, here it is of 10^8 . Five of the first 6 provinces in the solar production density (Saskatchewan, Manitoba, Alberta, Ontario and Quebec) appears in the graph, and only British Columbia is an outsider. A map with the same colours scheme logic is used to examine more accurately the distribution of this production on the territory.

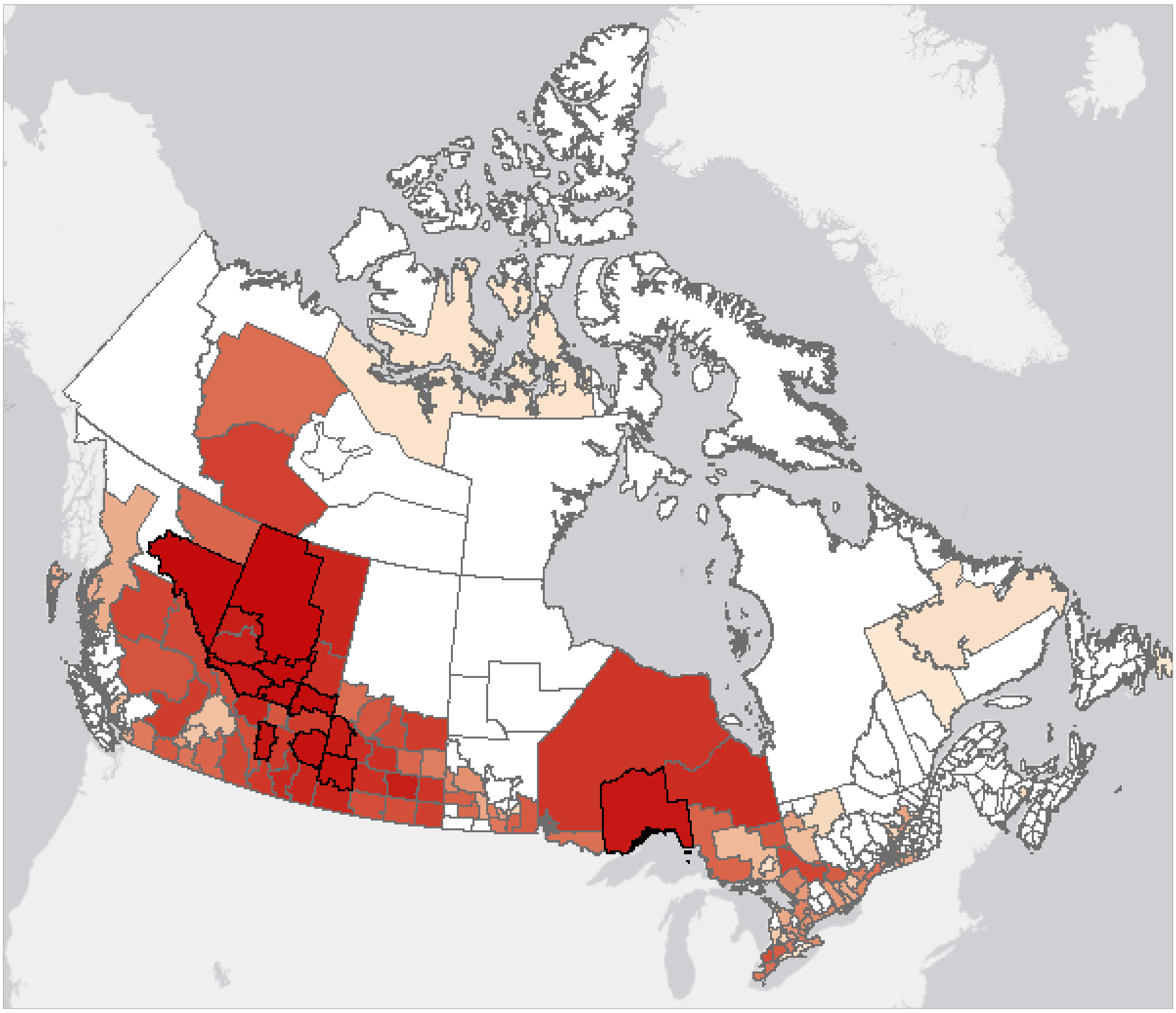


Figure 41 Distribution of zones for hydrogen production from solar resources according to 500 m buffer analysis

The distribution of colours remains almost the same of the wind one, being the natural gas network description the common determining element. But in the case of solar resources the spatial distribution was more defined than in the case of wind one, despite being the differences of production densities less strong. The effect of the surface is thus more relevant that the one in the wind case, both because not balanced by a density difference of the same order and because potentially promote the choice of not really profitable areas. The effect can be analysed using a table (table 15) with the same contents structure that the one used in the wind case. The areas are almost the same, with the exception of Saskatchewan No.6 substituted by Alberta No.14, thus this province gains another position in the ranking and rises to 7. Among them there is the division with the best production value with the Peace River division shift to the second. The impact of these 11 division on the hydrogen production and on the covered surface at 500 m remain the same, but it is interesting to notice the coincidence of the ranking for the two fields.

Province	Census division	Production [kg/yr]		Area [km2]		Density [kg/km2]	
Alberta	Division No. 17	1	1.650E+08	1	1542	93	107001
British Columbia	Peace River	2	1.489E+08	2	1519	130	98043
Alberta	Division No. 13	3	1.157E+08	3	1044	46	110841
Alberta	Division No. 10	4	1.096E+08	4	944	35	116141
Alberta	Division No. 11	5	1.042E+08	5	924	42	112694
Alberta	Division No. 4	6	9.773E+07	6	794	12	123029
Alberta	Division No. 6	7	8.371E+07	8	715	31	117097
Saskatchewan	Division No. 8	8	7.966E+07	10	640	7	124386
Ontario	Thunder Bay	9	7.734E+07	7	716	81	108040
Alberta	Division No. 14	10	7.039E+07	9	656	86	107252
Saskatchewan	Division No. 13	11	6.768E+07	14	556	16	121715
SOLAR		total	1.12E+09	total	10051	average	113295
		% 500 m	34	% 500 m	34	% 500 m	104

Table 15 Best 11 zones for solar hydrogen production at 500m buffer analysis

That is due to the lower level of the differences between zones density that determine a lower influence on final results. The proof of that effect is the absolute value of the total area, that rises with respect to the wind one. A higher surface of the Alberta No14 division (S6 at 520 km^2 and A14 656 km^2) determined its overcome in the ranking despite the higher potential of Saskatchewan No.6 (S6 at 124032 kg/km^2 and A14 at 107252 kg/km^2), while in the wind case the difference was high enough to prevent this effect. At the same time the density ranking shows some interesting position. Saskatchewan No.8 is the 7th in the 500m ranking, Alberta No.4 is 12th, Saskatchewan No.13 is 16th Also if many value remain below the median rank (72), the majority is above it and these three zones register a quite good density. That results in an average density slightly higher than the mean one, better than the wind result. So the lower differences penalize some areas, but at same time there is a general good availability of solar sources in the transmission lines surroundings. In particular it is interesting to explore the case of the three central Provinces, Alberta, Saskatchewan and Manitoba. The first are largely represented by the presence of the network, while in the third one only a small section is interest. Analysing the values of hydrogen production density of all the 293 census divisions, it emerges that the best 45 values are shared by these three Provinces, and in particular 9 in Alberta, 17 in Saskatchewan and 19 in Manitoba. This effect was expected from the initial analysis of data, but the method captures them only in the aggregative form of the provincial summary. The overall examination lead to a clear result: the most interesting areas for the hydrogen production from wind resources are the provinces of Alberta and Saskatchewan, located in their southern areas. A large production has been derived from British Columbia, but its production density is relatively lower than the one related to the winds resources. Manitoba could achieve a certain role of interest, but only with the further developing of the infrastructure. The result is almost equal to the one of the wind, with some minor exceptions.

3.2.3 Buffer results analysis

The results obtained from the spatial analysis, developed with the method of buffer and intersection tools, presents some elements that are common to the results of both the energy sources. They are in particular unified by the other two data set that has been used for the study, the one related to the pipeline path and the common spatial reference of the census division layer. The idea at the base of the developed method was to use this last one common reference as the way to unify the different data sources, with the consciousness that the choice of a division instead of another would have possibly determined a different result. The buffer tool should have been able to partially overcome the problem of the division choice, by determining a sort of measure of the availability of the infrastructure on a territory and how much resource would the transmission network cross in its spatial distribution. The element to analyse to understand how the method worked is how it has determined the results at each step: is there an exploration of the sources or is it the only land expansion to drive the increase? The answer is that once the characteristics of the areas surrounding the line have been established, the surface expansion become almost the only parameter that determines a production change. To proof this observation, it is displayed the following graph. It shows the growth of the hydrogen production at each increase of the buffer analysis range, weighted on the value of the previous step. The value roughly represents how many times the incremented value has to be increased of a value equal to itself to get the new one. It is not a proper a rate of change, that should be defined as the ratio of the difference and the difference between two relative reference (like the buffer distance or the area at that distances). They are also reported the data of the additional steps to have a more extended set of data. The abscissa axis is reported in logarithmic scale to have a better vision of the evolution for lower values.

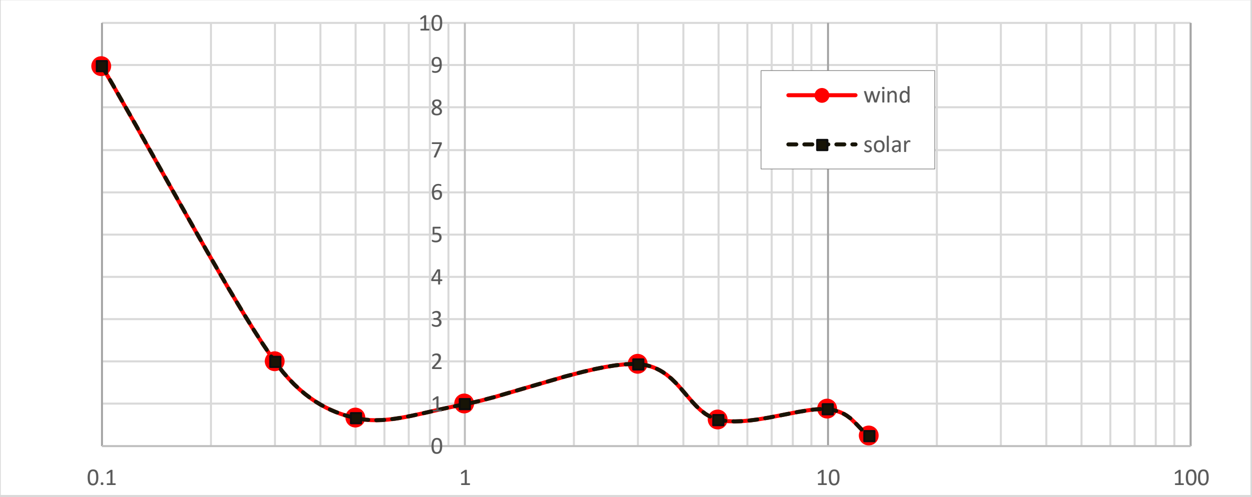


Figure 42 Relative increase of overall hydrogen production at each step of the buffer analysis

The increase in the steps are quite constant, with the exception of the first one from 10 m to 100 m. The interesting observation is that the amounts reported on the ordinate axis is also the rate of increase of the values on the abscissa axis. In other words the rate of increase of the hydrogen production is similar to the one of the distance. Displaying the same value for both the buffer range and the overall areas covered at each step, the graph change into this one (figure 43). They are used different styles and colours to get the idea of their overlapping, but the distance graph in reality partially departs from the others. At the same time the surface line match with the two of resources, and is quite an interesting relation. The difference between the distance and the surface, with the second lower changing rates than the first one, can be explained by two effects. The first is related to the shape: the increase of the two measures would have been the same only if the pipeline was a long straight line.

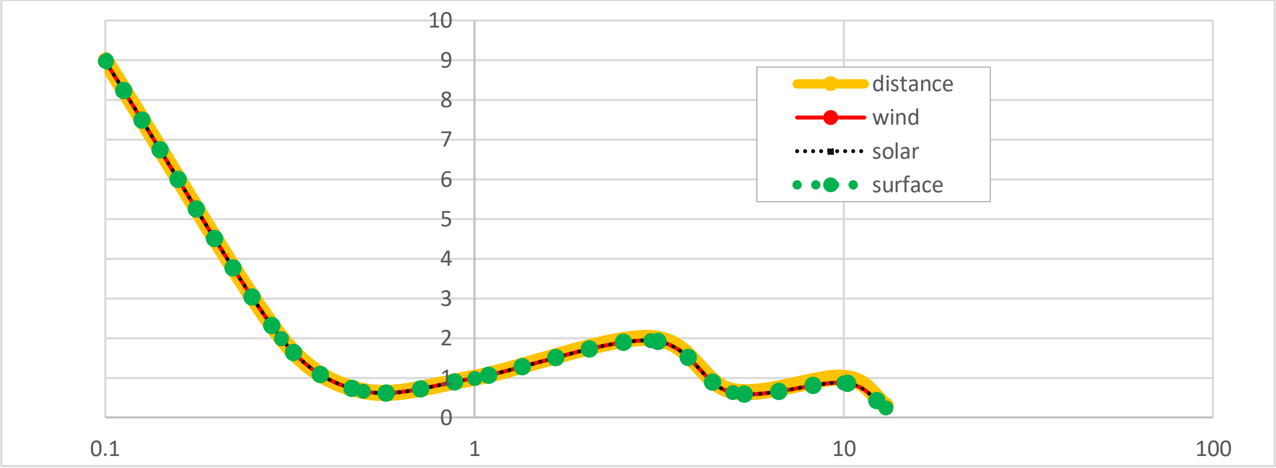


Figure 43 Relative increase of overall hydrogen production at each step of the buffer analysis, 2

But there are many deviations where the surfaces overlaps. The second is the effect of the overlapping related to the presence of pipelines that are close. That effect occurs particularly in the areas where the network becomes a dense grid, like in Alberta, Saskatchewan and north BC. The more interesting effect is the correlation between hydrogen productions and surface increase rates: their values for this parameter is almost equal, with an absolute error in the 10^{-3} order. The way surface expands at each step with respect to the previous one is the same way hydrogen production for both sources increases from one production to the other. But the first value is one of the two factors that define the second value, thus this is not simply a numerical correlation. The relation that exist between them is clearly visualized if they are disposed the two axis of the graph (figure 44).

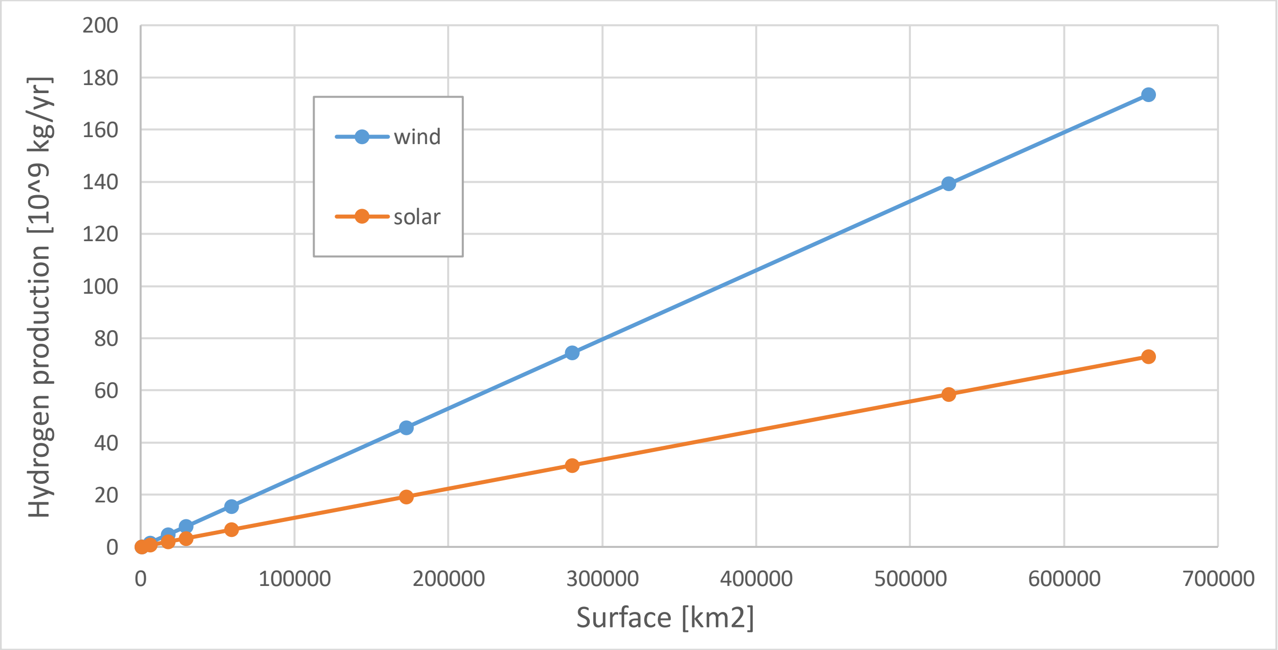


Figure 44 Hydrogen production and surface correlation analysis

The possibility of a linear correlation is quite strong and confirmed by the use linear regression functionality of the spreadsheet (Excel), that produces a linear function $R^2=1$ for both solar and wind source. Applying the values of surfaces at the obtained linear function, they are obtained values of production with an error of more than 13% with respect to the production values found using iteration. The correlation is not a way to simplify the solution of the problem with a simple function, but the signal on how the iterative process works in this specific case. If the relation with one of the two factor is almost linear, that means that the other factor remain almost constant, and the other factor are the wind and solar production densities. They can change only if the buffer expansion intersect a new zone, something that occurs in the steps of the study. The value of census divisions involved goes from 143 at 10 m to 144 at 0.5 km and then up to 176 at 13 km buffer range. So the method works in the exploration of the areas surrounding the pipeline path, but their impact is less relevant than the one of surface expansion. If it is considered the model of the linear regression as significative, the change in the hydrogen production densities should affect the constant that multiply the variable surface. When the linear regression is performed for each step of the method application, the results effectively changes every time. The constant is the inclination between two iterations, and can be defined as:

$$i_n = \frac{HP_{n+1} - HP_n}{S_{n+1} - S_n}$$

where *HP* is the hydrogen production and *S* the corresponding surface. It is something like an average value of the potentials among all the involved areas, as confirmed for the average values obtained: 265087 kg/km^2 for wind, 111516 kg/km^2 for solar. The values are similar to the national averages (275457 kg/km^2 for wind, 101904 kg/km^2 for solar) and within the range of production density values involved in the buffer analysis. The values obtained for each step interval are very close, but different. They are calculated these differences, and the following paths are obtained for the solar and wind case (figure 45).

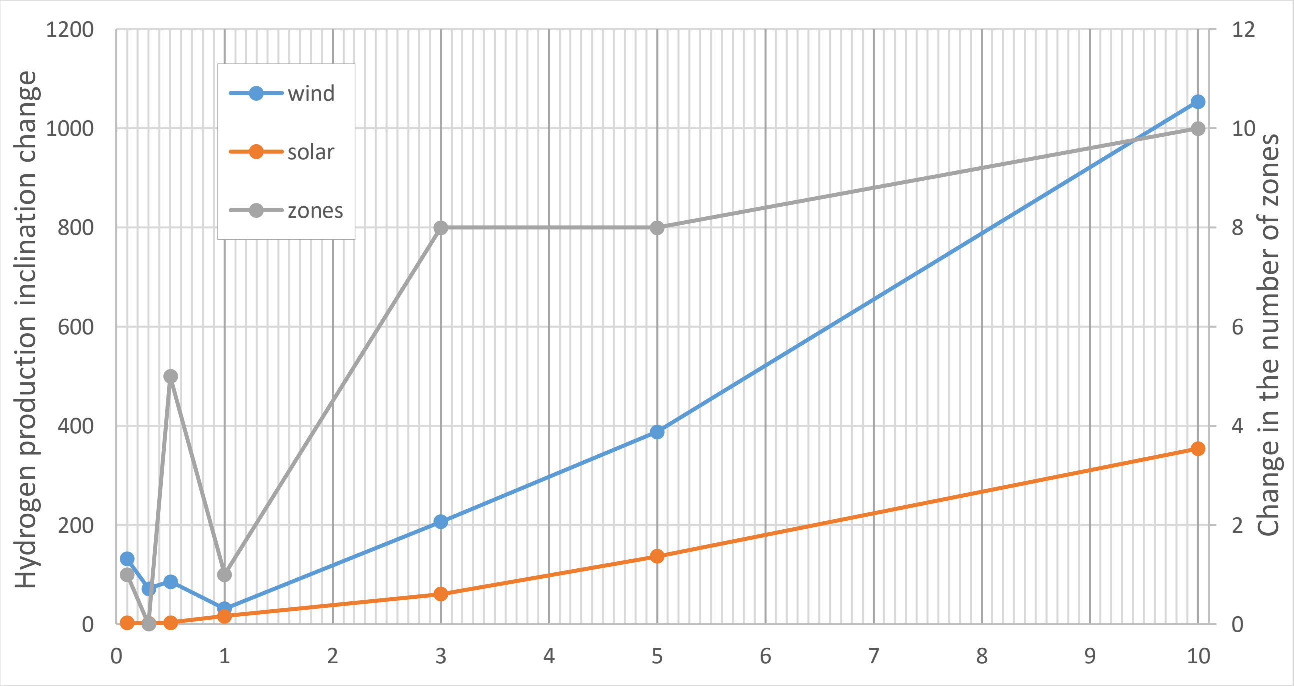


Figure 45 Effect of new zones involvement in the change of production

The variation of the inclination could account also for other effects than the introduction of a new potential in the form of a new zone. For example a difference in the increase rate of areas (eg for an overlay effect) does not maintain the ratios of surface share among the already involved zones. The grey line represents the number of new zones at each iteration of the method, at different distances. Its values are displaced in the secondary axis. There is not a perfect correlation, but a common path can be recognised among the wind and zones lines. It is relevant in this sense the different evolutions of solar and wind curves: while the values of the first grows more slowly and according to the spatial evolution, the wind one has a behaviour more similar to the grey line. It is relevant because it has been observed that the wind sources demonstrate a wider range of production density values, thus the involvement of a different zones should result in more effective impact on the average production density change. The limited change could thus be related to the similarity of the production density of near zones, so that the impact of a new zone is very low because of similar to the near one. The effect is particularly evident in the sun density, where the south-north growing path are homogeneous, while wind dispersion is less regular.

The outcome is also strengthened by the dimension of census divisions, that mix different values and eliminate local high difference that could have result in more irregular evolution of the surface-hydrogen production curve. That impact cannot be, in any case, too relevant. In fact it is weighted by its surface, and being a marginal area this weight will be lower than the already present one. That dynamic is particular relevant with the increase of the range and thus of the involved areas, when the weight of the initial zones is much larger than the new one. As already observed the effects are not unique and it is difficult to estimate the impact of a different production density inclusion. They should be measured the variations related to surface evolution, that as observed does not follow the proportion of the range enlargement for a variety of reasons (shape of the line, lines overlapping, the presence of water bodies that do not contribute to the areas calculations). The observation performed are driven by an analysis of the data evolution, but there could be the danger of a confirmation bias in the attempt to find correlations among data behaviours.

4. Conclusions

The work has been developed with the objective to individuate areas of Canadian territory of interest for the production of hydrogen from renewable energy sources and their injection in natural gas grid. Hydrogen (1.1.2) is considered as an important element for the decarbonization of different energy final use sectors. It can be produced starting from different sources, in particular from fossil fuels, biomasses and electricity. Its potential role can be achieved only with the production from emission free and renewables sources, thus mostly using RES generated electricity for water electrolysis production (1.1.3). That technical devices for its deployment are already available, but represents costly solutions and are sustained by a small industry that need to enlarge its scale to provide enough productive capacity and reduce costs. The energy market dynamics and the technology affordability make it difficult to implement hydrogen based solutions for final consumption. The integration in the energy sector can be achieved only with the development of a hydrogen infrastructure, to connect areas for the production on purpose and centres of consumption. Different alternatives are available for different solutions, and one of them is construction of hydrogen pipelines. An option available in short time, with potentially low expenditures and no major soil occupation is the gradual conversion of the natural gas infrastructure (1.1.4). It is not possible to deliver pure hydrogen but a certain percentage could be admitted. The limitations are different for the different element and devices of the network, and dedicated regulations, norms or standards has not been developed. Nevertheless institutions and companies are deploying a growing number of experiences to solve the solution uncertainties and unlock the application potential.

Among them there is not Canada (1.3), which energy system largely rely on fossil fuels and is among the major GHG emitters, both in extensive and intensive (per capita and on GDP) estimations. Its power production is already largely based on zero emission sources, mostly hydroelectric and nuclear. But the integration in other sectors is relatively low and it is the object of last climate action politics. Hydrogen is not on the country radar as a major solution, but at same time important companies operates in the sector. Another important element is the extent of the natural gas infrastructure, that moves the gas produced in north British Columbia, Alberta and Saskatchewan in the east of the country and to the American market. It could be used for the purpose and to develop the renewables in the central areas of the country, that are national top emitters and lower RES producers. Also in this case there are no norms or standards, but only a series of limits related to the structure of the infrastructure [29]. To analyse the potential energy sources that could be used for that purpose, they have been used Geographic Information System (GIS) data (1.2). This one conjugates the spatial and geographical reference to the informations on the territory of interest. The elaborations has been performed using the software ArcMap 10.6, of the ArcGis Desktop suite, and applying the workflow of the Spatial analysis. The method developed combines both the software tools for the spatial analysis and the knowledge about the production chain that links renewables potential and hydrogen production.

The first numerical results of the study are the distances between which it is possible to accomplish the production levels required by injection percentages. They are really small if compared to the total length of the pipeline or to the sole dimensions of the plant require for the production. Their value are justified by the meaning of the defined area, considered as covered by solar or wind farms on both side of the path. Without the surface exclusion all the available area is considerate as an empty plane suitable for the production. The implementation of this degree of detail, for example by reducing zone surface according to significative values by Province, would have provide a more realistic result. From the comparison of the overall energy and hydrogen outcomes with those of other studies or of the Canadian energy system it emerges how the results obtained are out of the scale of the exploitable sources. That is precisely due to the avoidance of any land exclusion. The objective of the study is not to give a precise measure of this sources, but to explore their location and for that purpose the relative differences responds to the needs. At the same time an upper bound of the available wind and solar sources is provided, and despite being optimistic they has been obtained with real or proved data and following appropriate methods.

The results obtained are in any case meaningful, because the territory is explored, following the path of the transmission line, looking at the overall potential of large zones. The areas that emerged from the study are the most interesting for a possible future development of RES in that direction. They are Alberta and Saskatchewan, with some good potential in Ontario too. This is an interesting case for many reasons. First of all the presence of good wind and high solar potential production was not unexpected. While wind resources are better in other areas, like the Atlantic Provinces and northern Quebec, solar one are the best available on large scale in the country. That is not new for the provincial government, that already consider them important to achieve the provincial climate targets for 2030 [71], betting mainly on the possibilities of solar photovoltaic. The outcome obtained from wind sources was mostly justified by pipelines network extension, but the one on solar is plenty representative of a concrete potential, as demonstrated by the proper tables. If the production from wind is higher, the profitability could reward solar one for their intensity. The level of available production will not be equal to the one estimated, but the availability of large territories with a low population make these areas very interesting for further development in this direction.

The other aspect of the result are the pipelines, that cover large areas of the provinces to connect with the natural gas production fields. The untold assumption of the study is that the lines would be available for the injection. It was partially analysed the legal and technical aspect of the problem, and the economical too considering the profitability of the injection. But another aspect that involves both the fields is the position of the natural gas producers. The injection would for sure rise the cost for natural gas end users, while reducing the energy content on volume. They could see a decrease in their revenue due to the increase of prices and possible decrease in consumption. A similar issue has already risen for the carbon tax, that will determine an increase in transportation fuels prices. At the same time Canadian natural gas producers, concentrated in Alberta, British Columbia and Saskatchewan, are facing growing problems with their business. They are mostly related to the increase of USA production of natural gas from unconventional sources [70]. The export to the American market and even to the internal west markets decreases in past years, with a consequent decrease of revenues. The solutions that they foresee is to direct exports to Asian countries, where the demand continues to rise, via LNG terminals on the west coast. The hydrogen injection practice would be a measure in contrast with their interest, creating a competitor on the same dispatching infrastructure. At same time it could be a possibility to develop the production of hydrogen from NG with CCUS, but that is an hypothesis not analysed in the study.

The result of British Columbia, which is 1st in the wind and 2nd in solar ranking (at 500m), is ambiguous and expose the limits of the study. It is at the same time respectively 122nd and 130th in the hydrogen production density ranking, among the worst areas, while having the 2nd position in the buffer analysis defined surface (500 m). The outcome is in this case due only to the spatial extension across the census division zone. For each zone the overall surface potentially determine an higher buffer area, because a bigger pipeline section can be contained within. At the same time big areas determine a lower detail of the production density description, thus a homogenization of both higher and lower values. The effect should compensate in the determination of buffer areas and their use for hydrogen production calculation. But in this case and partially in all the best performing zones, it is the only surface value to determine the good result. In the light of the method logic it is correct, because the bigger area signals the presence of the near infrastructure and thus the higher potential interest for hydrogen injection. At the same time it penalise too much the resource intensity in favour of the extensive variable. That is why the result obtained as a combination of the two elements has to be examined considering the production density parameter, as an index of the average resource quality.

A possible alternative could has been the choice of a spatial division with constant areas, a sort of raster layer, with the possibility to maintain one of the two parameters constant. Not considering the inequality produced by the country boundaries, that are not completely regular, the alternative could has been interesting and exploit at the same time the more detailed characterization of density and the lower impact of surface value on single division. The choice done is justified by the possibility to use a division not only ready to use and compatible with statistical categorizations, but already employing a series of useful spatial differentiations, like the one between north and south of the country. The impact of the areas and of hydrogen production density has been the object of a deeper analysis (3.2.3), that resulted in the evidence of an almost linear correlation between surface expansion and hydrogen production. The effect in that case is not on the single division, but on the aggregated value, and it is related to the scarce exploration of different values obtained with the method. With a denser division a less regular growing path should result from the more frequent variation of production densities. In fact the correlation between the number of involved zones increase and linear constant variation is stronger is more evident with the wind source, that has a bigger and more irregular variation of the values with respect to solar one. In any case the impact of the division on this phenomena can never be too important. Whit exception of exceptionally different hot spot (or cold spot), the evolution of the characteristics across the territory is usually smooth or at least regular. The conclusion is that a division with smaller zones would have affect the identification of the specific zone, but with lower impact on the values of buffer range or of the results in macro areas with similar geography. In the case study this areas are roughly represented by provincial division, and a cumulative analysis would have result in the identification of Alberta and Saskatchewan in any case.

The other results of the study are obtained from the provincial aggregation of the outcomes. Ontario rank 3rd in both solar and wind cases, with the presence of Thunder Bay in the production ranking. The province is already the 1st one in Canada in term of installed wind turbines capacity, followed by Quebec and Alberta [68]. While Manitoba shares some of the characteristics of the other central provinces, Quebec results only 6th for the good solar and wind resources in the south part of the province. It will be largely impossible to exploit these resources, that are located in the densely populated line between Lakes and Saint Lawrence river. At the same time they remain unexplored the big resources of its north, as well as other areas across the country with good potentials, especially for the case of the wind. The results of the production all across Canada have been reported to have an idea of the country potentials, but only the areas resulted from the study can be considered of interest. The problem is not only related to the objective of this report, by on the nature of Canadian territory dimensions. The distances are huge and the idea to get resources far away for the injection in the grid is not feasible. To use the distance as a parameter made possible to include only areas that can be used for the production. Other drivers could have been used, maybe less geometrically driven. But as simple as that one is, the distance between two points is, on this scale, a good parameter to estimate the possibility to easily connect them. That is particularly true if considered that this surfaces develop a transmission pipeline, an infrastructure that in the majority of cases does not cross territories with extreme shapes. The definition of the precise location for possible future projects will be performed with more detailed analysis, at a lower dimension than the national one. They will consider the land exclusion and the local wind and solar conditions.

In conclusion the objective of the study can be considered fulfilled. Areas of interest for the potential development of hydrogen production from wind and solar sources has been founded, accounting their availability for the injection in natural gas grid with the proximity method of buffer analysis. The method developed can be replied in other contests and territories to explore the availability of renewable energy sources, or more in general the availability of sources around a certain infrastructure. The effects related to the spatial partition are specific both of the case study, with the way the resource change its availability across a territory, and of the chosen spatial partition, that affect both the level of detail and the buffer range progression. The values obtained are not significative for their value, but for the potential they signal on a territory. The provinces in the west, Alberta, Saskatchewan and partially Manitoba are those that can benefit more of the resources and transmission pipeline contemporary presence. The first two in particular could slowly convert to hydrogen production industry, converting part of the natural gas extraction industry that is facing a demand decrease. Ontario and partially Quebec too have good potentials while British Columbia, with the majority of territory crossed by Rocky Mountains, have only low intensive sources despite an interesting pipeline coverage. Canada climate action has to face the transition of its fossil fuels productive system and of a large part of final consumption to carbon zero sources of energy. The use of hydrogen, sustained by federal incentives in early stages, can be the solution for the country critical sectors. The industrial forces with the right expertise are already in place in the country, and the hydrogen injection in natural gas grid could be the early stage for a wider transition.

Appendix A

Figure A1 Wind mean annual speed at 100 m, raster layer

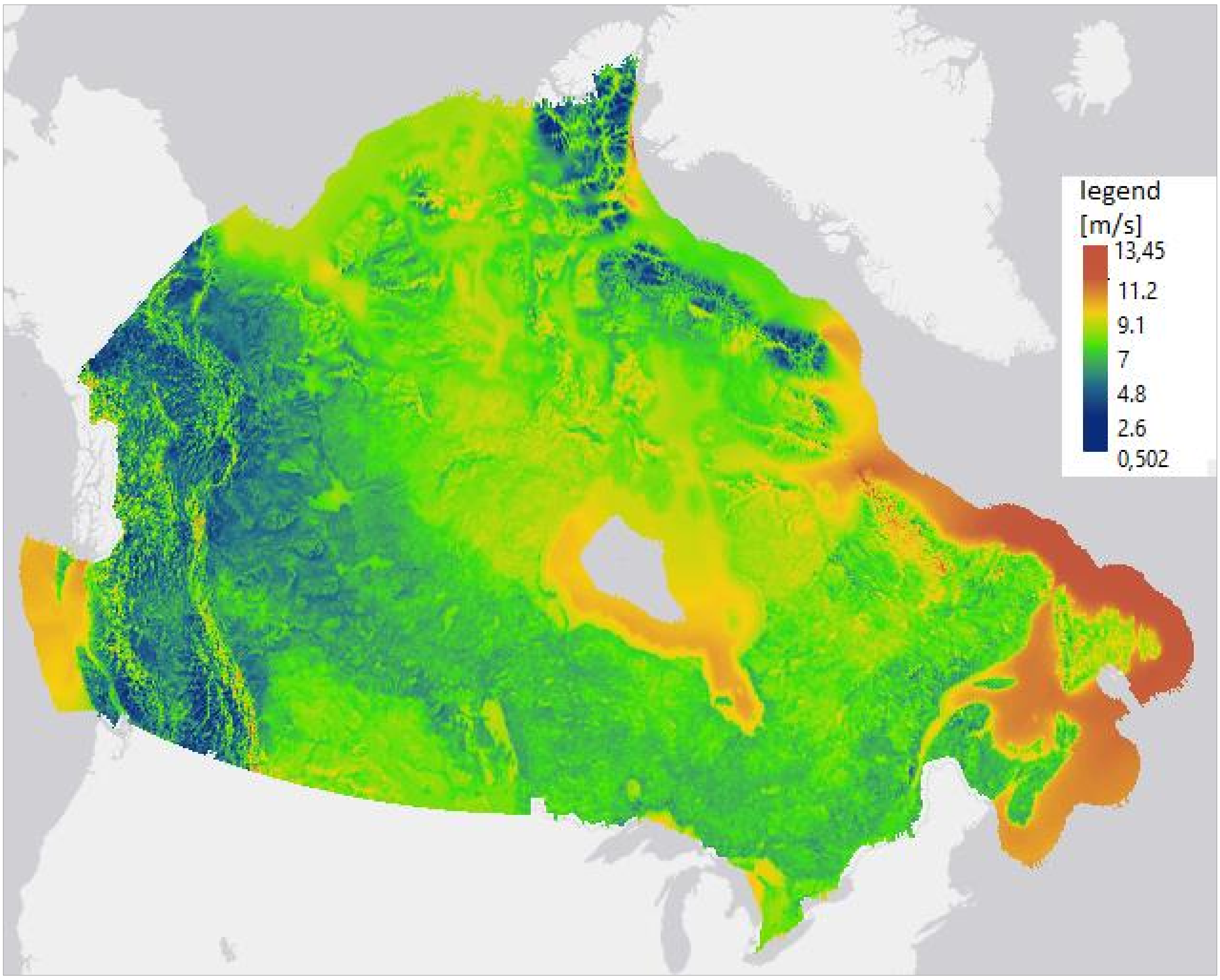


Figure A2 Wind mean annual speed at 100 m, mean value polygons layer

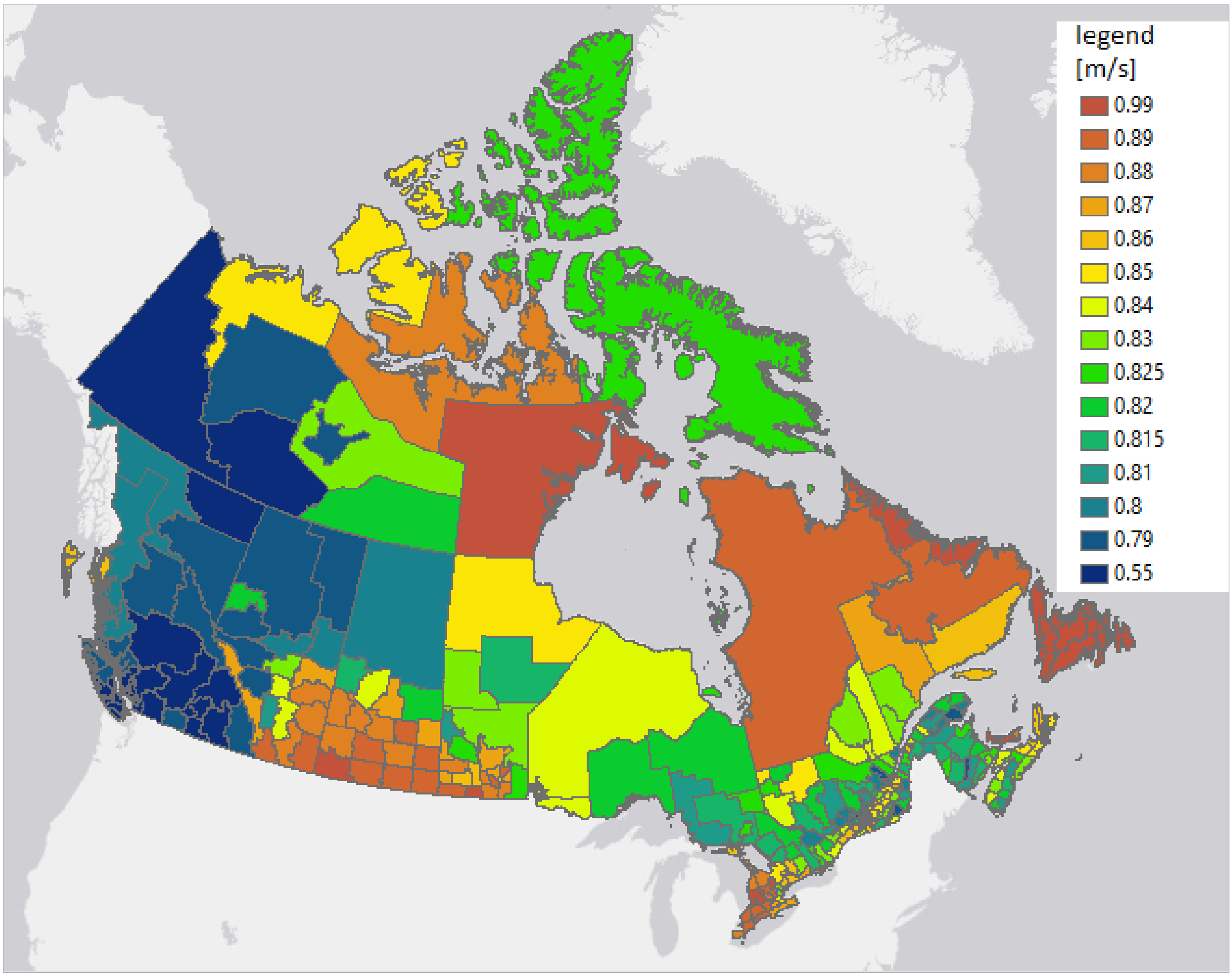


Figure A3 Solar annual photovoltaic power potential , raster layer

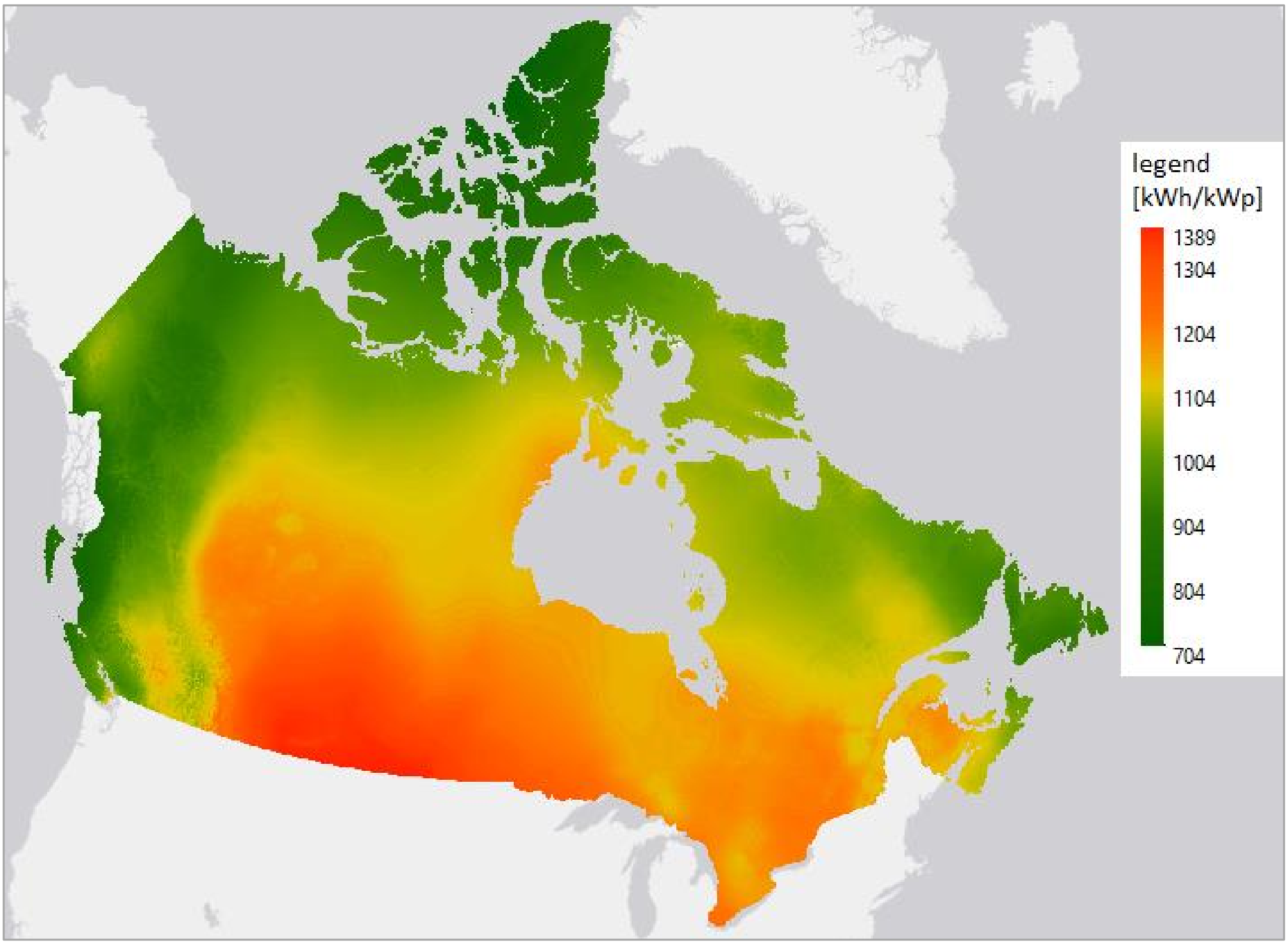
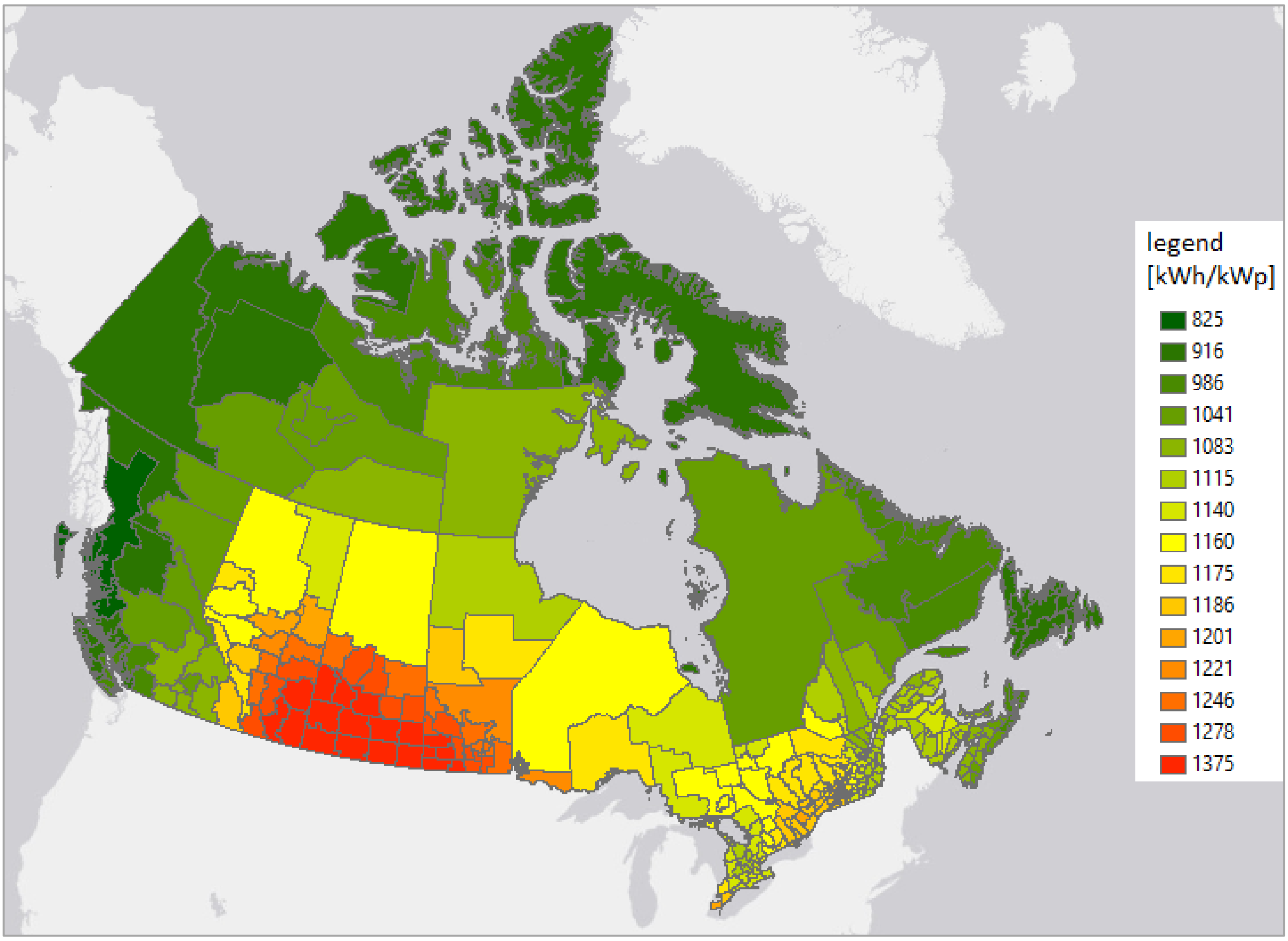


Figure A2 Solar annual photovoltaic power potential , mean value polygons layer



Appendix B

Table B1 Energy production at different buffer distances by wind and solar sources

[Mwh/yr]	10 m	0.1 km	0.3 km	0.5 km	1 km	3 km	5 km	10 km
Wind	8.63E+06	8.61E+07	2.57E+08	4.28E+08	8.51E+08	2.50E+09	4.06E+09	7.59E+09
Solar	3.63E+06	3.62E+07	1.08E+08	1.80E+08	3.58E+08	1.05E+09	1.71E+09	3.19E+09
Total	1.23E+07	1.22E+08	3.65E+08	6.07E+08	1.21E+09	3.55E+09	5.76E+09	1.08E+10

Table B2 Hydrogen production at different buffers distances by wind and solar sources

[kg/yr]	10 m	0.1 km	0.3 km	0.5 km	1 km	3 km	5 km	10 km
Wind	1.58E+08	1.58E+09	4.72E+09	7.85E+09	1.56E+10	4.58E+10	7.44E+10	1.39E+11
Solar	6.65E+07	6.64E+08	1.98E+09	3.30E+09	6.57E+09	1.93E+10	3.13E+10	5.86E+10
Total	2.25E+08	2.24E+09	6.70E+09	1.11E+10	2.22E+10	6.51E+10	1.06E+11	1.98E+11
[m^3/yr]								
Wind	1.87E+09	1.87E+10	5.58E+10	9.28E+10	1.85E+11	5.42E+11	8.80E+11	1.65E+12
Solar	7.86E+08	7.85E+09	2.35E+10	3.90E+10	7.76E+10	2.28E+11	3.70E+11	6.92E+11
Total	2.66E+09	2.65E+10	7.93E+10	1.32E+11	2.62E+11	7.70E+11	1.25E+12	2.34E+12

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