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ThermoGIS: from a Static to a Dynamic Approach for National Geothermal Resource Information and Development

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ABSTRACT

Geothermal development in aquifer settings can benefit considerably from a wealth of subsurface data acquired over the past decades by oil and gas exploration and production. In the Netherlands, this data has been gathered by the Geological Survey and has been made publicly available (www.nlog.nl). Almost a decade ago this data was used to create nationwide maps to identify prospective potential of clastic aquifers. It includes key parameters such as: depth, thickness and permeability, as well as aquifer temperature maps from a 3D temperature model of the subsurface. A techno-economic tool complemented these maps to identify prospective areas for geothermal heat extraction, which could be used for feasibility studies and site selection. In the past years, the information system and associated tools (www.thermogis.nl/en) have promoted geothermal development in the Netherlands, marked by a spectacular growth from a few to tens of doublets, mostly used for the heating of green houses.

In recent years, a number of shortcomings and potential additions have been identified which would significantly improve the reliability and capabilities of the information and tools provided in ThermoGIS. These have been implemented and released in a completely updated version and web portal, available online since Q4 2018. This allows for continuous and dynamic updates when additional information both from relevant internal and external sources becomes available. The update includes a fully revised workflow for mapping of flow properties and underlying uncertainty, new data from operational geothermal doublets, and a fully revised techno-economic performance tool incorporating the latest insights in cost parameters, innovative development options (e.g. including heat pump and well stimulation scenarios) as well as up-to-date feed-in and taxation schemes. Further additions are foreseen to assist policy makers in developing scenarios to speed up the development of geothermal potential, as well as to unlock areas which are underexplored and in need of further investigation. Furthermore, it is anticipated that ThermoGIS information and tools are of significant value for the foreseen development of district heat networks as part of the large-scale switch from gas-fired to renewable heat and large-scale seasonal heat storage in the subsurface.

1. INTRODUCTION

The three main sources of renewable energy in the Netherlands are biomass, wind and solar energy. Geothermal energy is fourth and has a large unused potential. One of the main obstacles for the development of this potential is the uncertainty related to the subsurface conditions: for geological reasons, not all locations are suitable for the extraction of geothermal energy. Fortunately, there is a large amount of subsurface data available as a result of the search for oil and gas, and the Dutch mining law from 2002, which states that all acquired subsurface data becomes publicly available after 5 years.

The geothermal energy sector in the Netherlands is relatively young, with the first producing doublet dating back to 2007. The existing geothermal doublets are mostly used to directly heat green houses. There are other possible applications such as district heating. Most developers of geothermal energy do not have subsurface evaluation expertise as their core business and they are usually interested in the development of a single geothermal installation for local use. This lack of subsurface knowledge and experience stands in the way of a quick further development of the sector.

ThermoGIS provides a regional geothermal resource assessment, using the publicly available subsurface data, which could facilitate in providing relevant information suited for stakeholders with limited subsurface expertise. The initial version was released in 2012 (see Bonté et al. (2012), Pluymaekers et al. (2012), Kramers et al. (2012) and Van Wees et al. (2012)). Version 2.0 became available in October 2018. The complete workflow has been considerably improved with updated methods for property mapping, incorporating newly available data, and a fully revised techno-economic performance tool. The results are available online through a completely redesigned user interface. Because of automatization and ability to run parallel on multiple cores, it allows for regular updates in the future. The method and maps described here correspond to version 2.1 released in March 2019. The maps can be viewed on www.thermogis.nl.

2. METHODOLOGY

In this section we will discuss the full workflow. The first step is to select a list of possible geothermal aquifers. The ThermoGIS workflow, outlined in Figure 1, is applied to each of these aquifers.

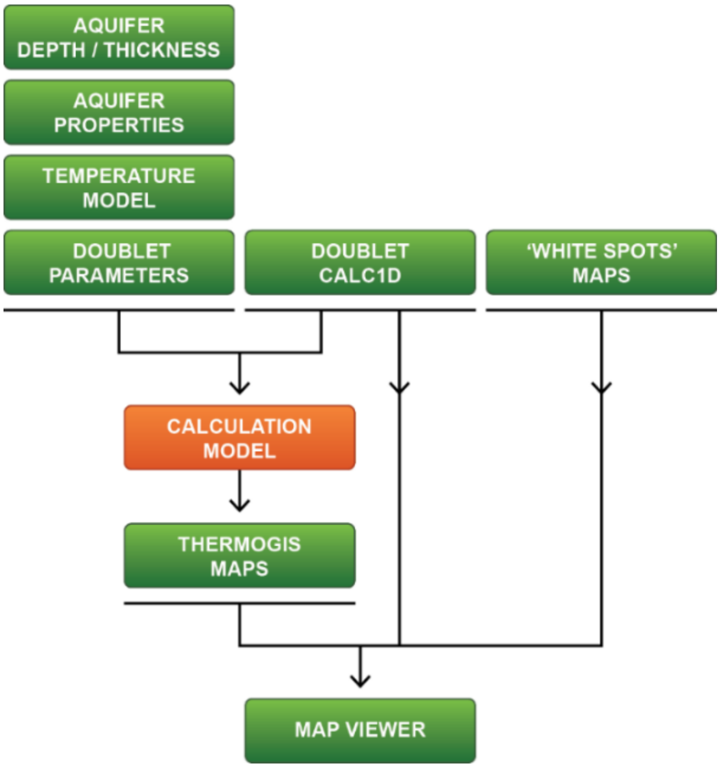

Figure 1: ThermoGIS workflow: DoubletCalc1D is a 1D flow modelling module that is used in the calculation model, see section 2.5.

A 2.5D geological model is created consisting of the thickness, depth, net-to-gross, porosity and permeability of each aquifer. This serves as input for the techno-economic analysis (calculation model), together with a 3D subsurface temperature model, technical doublet parameters, installation costs and economic parameters. The workflow is automated in such a way that updating the maps to incorporate new insights or new data can be done relatively quickly. The transmissivity (thickness x permeability) is the parameter with the largest uncertainty. The transmissivity uncertainty is taken into account in the calculations resulting in P90, P50 and P10 output maps. In the next section each of the steps is discussed in more detail.

2.1 Potential aquifers

The thickness, depth, permeability and temperature are the main geological criteria which determine whether a specific subsurface layer is suitable for geothermal energy extraction or not. In the Netherlands there are many layers that are potentially suitable for geothermal energy extraction.

For the ThermoGIS calculations, 29 layers have been selected. The 29 layers have also been stacked into 5 aggregate layers comprising several aquifers (see Table 1). The codes correspond to the Nomenclator of the Netherlands (TNO (2019)). Stacked layers have been created for layers that could produce simultaneously with one producer-injector combination.

Layers shallower than the Paleogene Someren Member have not been considered in this approach because the expected temperatures are too low for conventional geothermal energy extraction. Layers older than the Lower Carboniferous Zeeland Formation are also not considered due to lack of data. In fact, the Zeeland Formation itself is treated with an alternative workflow since there is not enough data available to follow the standard workflow.

2.2 Geological model

The geological parameters required for the techno-economic calculation are:

- Thickness and uncertainty
- Depth
- Net-to-gross
- Porosity
- Permeability and uncertainty
- Temperature

Where the aquifer is thought to be absent, the grids are undefined. The porosity maps are not used in the techno-economic calculations directly, but they are used in creating the permeability maps.

Table 1: ThermoGIS aquifers, the codes correspond to the Nomenclator of the Netherlands, see TNO (2019).

age	formation / member code	formation / member name	stacked layers
Tertiairy	NMVFS	Someren Member	Middle & Lower North Sea Groups
	NMVFV	Voort Member	
	NMRFT	Steensel Member	
	NMRFV	Vessem Member	
	NLFFS	Brussel Sand Member	
	NLFFD	Basal Dongen Sand Member	
	NLLFR	Reusel Member	
	NLLFS	Heers Member	
Upper Cretaceous	KNGLG & KNGLS	Holland Greensand & Spijkenisse Greensand Members	Rijnland Group
	KNNSG	Gildehaus Sandstone Member	
	KNNSL	De Lier Member	
	KNNSY	IJsselmonde Zandsteen Laagpakket	
	KNNSB	Berkel Sandstone Member	
	KNNSR	Rijswijk Member	
	KNNSF & KNNSP	Friesland & Bentheim Sandstone Members	
Upper Jurassic and Lower Cretaceous	SLDN (SLDNA & SLDND)	Alblasserdam & Delft Sandstone Members	
Triassic	RNROF	Röt Fringe Sandstone Member	Upper & Lower Germanic Trias Groups
	RNSOB	Basal Solling Sandstone Member	
	RBMH	Hardegsen Formation	
	RBMDU	Upper Detfurth Sandstone Member	
	RBMDL	Lower Detfurth Sandstone Member	
	RBMVU	Upper Volpriehausen Sandstone Member	
	RBMVL	Lower Volpriehausen Sandstone Member	
	RBSHN	Nederweert Sandstone Member	
Permian	ROSL & ROSLU	Slochteren Formation & Upper Slochteren Member	Upper Rotliegend Group
	ROSLL	Lower Slochteren Member	
Carboniferous	DCH (DCHS & DCHL)	Hunze Subgroup (Strijen & De Lutte Formations)	Limburg Group
	DCD (DCDH & DCDT)	Dinkel Subgroup (Hellevoetsluis & Tubbergen Formations)	
	CLZL	Zeeland Formation	

2.2.1 Thickness and depth

For the thickness and depth maps, the deep Digital Geological Model, DGM-deep v4.0 (TNO (2014)), is used as a basis, which consists of depth and thickness grids at (Main) Group level. The layers of DGM-deep v4.0 model are based on extensive seismic interpretation and are calibrated with about 800 wells. For ThermoGIS, the areal extent, thickness and depth of the Rotliegend, the Zechstein and the Lower Cretaceous, were updated with respect to DGM-deep v4.0 using the interpretation of confidential wells released by the operator for this purpose.

A Group may consist of multiple aquifers and aquitards. The depth and thickness of the aquifers that exist within the (Main) Groups were modelled for ThermoGIS using information of 3855 wells, which is significantly more than the 800 wells that were used for the calibration of DGM-deep v4.0. Therefore, discrepancies may exist between the two models. Kriging and convergent gridding are used to create thickness maps from the well data points. This also yields a variance, which is used as uncertainty in the subsequent calculations. This uncertainty represents the aerial interpolation uncertainty and not the uncertainty of the well data points themselves.

2.2.2 Net-to-gross

The net thickness of the aquifer is determined by multiplying the gross thickness with a net-to-gross ratio. Due to the lack of a reliable, consistent net-to-gross database, it was decided to determine, for each aquifer, a single net-to-gross value, based on geological knowledge and available net-to-gross data. The Delft Sandstone and Alblasserdam Members (Nieuwerkerk Formation) constitute an exception to this rule. Using a reliable database, a net-to-gross map was generated for these aquifers.

2.2.3 Porosity and permeability

The porosity and permeability maps were created using data from all publicly available onshore wells. For the selection of data points, a ranking order was used that is based on the analysis type, which is linked to accuracy. In order of decreasing accuracy, the order is:

Porosity:

1. Full petrophysical analysis
2. LogQM average, calibrated using core plug data
3. Petrophysical analysis of the pay zone only
4. Core plug data average
5. LogQM average, not calibrated using core plug data

Permeability:

1. Well test analysis
2. Petrophysical analysis
3. LogQM average
4. Core plug data average

LogQM is a tool developed by TNO that calculates aquifer porosity and permeability averages from logs and core plug data in a semi-automatic fashion. Not all data points have been used for generating the maps. The main reason for ignoring a data point is when its value is anomalous and can be considered as unrepresentative for the regional trend.

No porosity and permeability maps have been made for the Dinantian reservoir. The carbonate rocks of this unit have very low primary porosities and permeabilities. However, these rocks sometimes may have secondary porosity and permeability due to dissolution and/or faulting. The spatial distribution of this type of permeability is very heterogeneous. The techniques that are used for calculating permeability maps of the other (clastic) aquifers is unsuitable for the Dinantian aquifer, for which only depth and thickness maps are produced.

For most layers a data driven geostatistical workflow is used to generate regional porosity and permeability maps (Figure 2). Exceptions are the Paleogene (Middle & Lower North Sea Groups) and the Nederweert Sandstone which are based on depth-porosity-permeability relationships due to lack of data. The standard workflow (Figure 2) uses co-kriging to combine average well porosities and a maximum burial depth map (A in Figure 2) to generate the porosity maps per layer (B in Figure 2).

A porosity-permeability relationship can be determined from core plug data. Often this relationship is assumed to be linear, however for ThermoGIS a polynomial trend was fitted to the average reservoir core plug measurements (Figure 3 and C in Figure 2) as described by TNO and EBN (2016). Applying this trend to the regional porosity map yields a trend permeability map (D in Figure 2). Residuals between this map and the average well permeabilities are kriged (E in Figure 2) and added to the trend permeability map resulting in a final permeability map (F in Figure 2) that follows the porosity trend while honoring the permeabilities measured in the wells.

The permeability standard deviation is calculated by combining the kriging standard deviation of the porosity maps and the uncertainty assigned to the porosity-permeability relationship. Generally, the uncertainty is larger moving away from well data points.

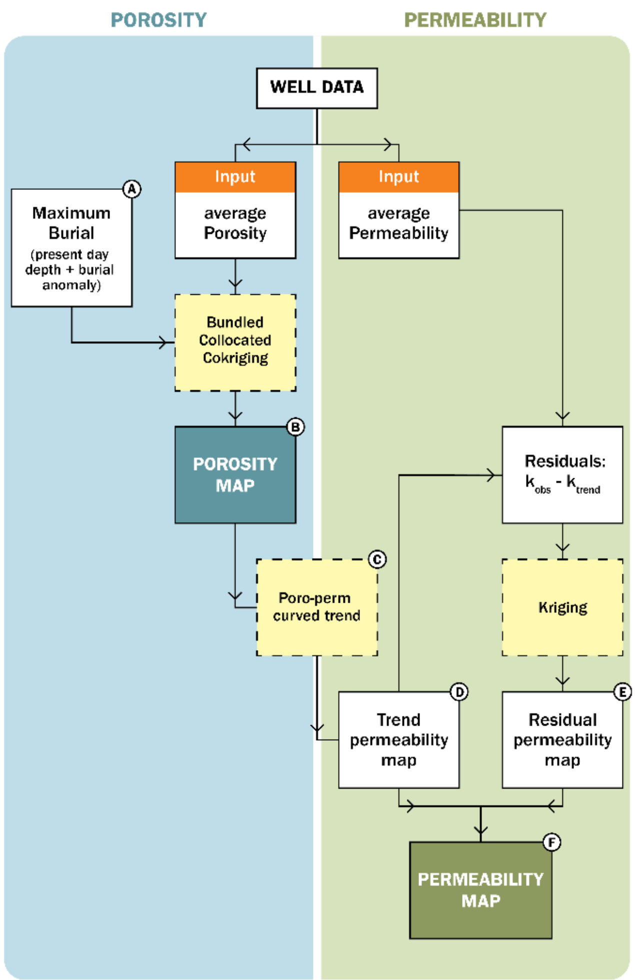

Figure 2: Porosity (left) and permeability (right) calculation workflow.

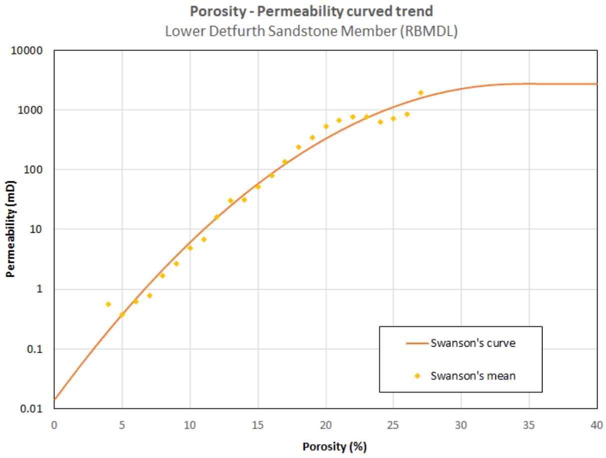

Figure 3: Curved porosity-permeability relationship based on Swanson's mean of core plug measurements of the Lower Detfurth Sandstone Member.

2.2.4 Stacked layers

Stacked layers have been created to account for producing several aquifers simultaneously with one producer-injector combination. Net thicknesses of the contained aquifers are added to obtain the stacked thickness. As a result, all stacked aquifers have a net-to-gross of 1. The stacked permeability is calculated by taking the weighted average of the permeabilities, using the net thickness as weight. To calculate the thickness and permeability uncertainties from the containing aquifers, the following formula is used:

$$SD_{stacked}^2 = \sum_{i=1}^{N} SD_i^2 + 2C \sum_{1 \le i < j \le N} SD_i SD_j \qquad [1]$$

where SD is standard deviation and C is the correlation factor. In this approach, the correlation factor is set to 0, meaning that the properties of the contained aquifers vary independently of each other.

2.3 Temperature model

A 3D temperature model of the subsurface is used to predict the reservoir temperature at depth. To generate this model, an initial temperature model was created, which was subsequently updated to match about 1300 temperature measurements, as described in Békési et al. (2019). These temperature measurements include temperatures from producing geothermal wells, and from less reliable bottom hole temperatures and drill stem tests from oil and gas wells.

The DGM-deep v4.0 model (TNO (2014)) was used to populate an initial model containing thermal conductivity and radiogenic heat production. By solving the heat equation in multi-1D, the prior thermal properties are calculated without taking into account the temperatures measured in the wells. The model-well temperatures misfit is then reduced by a number of data assimilation steps using the ensemble smoother with multiple data assimilation (Emerick and Reynolds (2013)). The workflow starts with a low-resolution model to incorporate effects of the deeper crust down to the lithosphere asthenosphere boundary. The model is then limited to 10 km depth to allow for a higher resolution final model (see Békési et al. (2019)).

2.4 Heat maps

Two subsurface heat maps have been created which are useful for determining the geothermal potential: the heat in place and the potential recoverable heat. The heat in place is the heat content of the reservoir with respect to the surface temperature in GJ/m^2 (see Kramers et al. (2012)). The potential recoverable heat is the heat which can be extracted from the reservoir, unconstrained by technical or economic limitations. It is assumed that the potential recoverable heat is 33% of the heat in place with respect to the reinjection temperature (Van Wees et al. (2012)).

2.5 Potential maps: techno-economic model

Economic potential maps for "direct use" geothermal energy (i.e., the produced heat being used *as such*: no electricity is produced) constitute one of the most important results of ThermoGIS. These maps are the result of a techno-economic analysis. The techno-economic model is run for each aquifer and per 1x1 km grid cell. Areas with hydrocarbon accumulations are excluded from the calculations.

First, the technical feasibility of hot water production is calculated in the technical model using DoubletCalc1D (1D geothermal power calculation tool, see TNO (2014) and Van Wees et al. (2012)). Next, the economic potential is calculated via the unit technical cost in a discounted cash flow model.

It is assumed that the uncertainty in the analysis is mainly caused by uncertainty in the transmissivity (thickness x permeability) of the geothermal aquifer. Alternative scenarios are run to investigate the effects of well stimulation and the addition of a heat pump on the geothermal potential in the Netherlands.

2.5.1 Technical model

DoubletCalc1D is a software tool that models reservoir and well flow in 1D. Table 2 lists the required input parameters. The geological model described earlier supplies the values indicated as ‘from map’. The return temperature is the temperature of the water being reinjected into the aquifer via the injector well. If a heat pump is added to the system, the aquifer temperature can be lower than the return temperature. A standard well configuration is assumed with parameters as listed in the table. A skin factor of -1 is assumed, corresponding to a 45° angle of the well in the reservoir. The calculation segment length is a setting in DoubletCalc1D.

Table 2: Technical parameters used in the batch DoubletCalc1D calculations.

technical parameter	value	unit
aquifer top depth	from map	m
aquifer thickness	from map	m
aquifer thickness uncertainty (SD)	from map	m
aquifer net-to-gross	from map	-
aquifer permeability	from map	millidarcy
uncertainty in natural logarithm permeability	from map	ln(millidarcy)
aquifer temperature	from 3D model	°C
aquifer water salinity	depth dependent	ppm
aquifer kh/kv ratio	1	-
return temperature	30	°C
minimum aquifer temperature	20	°C
distance between the two wells	optimized	m
pump system efficiency	0.6	-
production pump depth	500	m
pump pressure	optimized	bar
well trajectory curvature factor	1.1	-
calculation segment length	50	m
outer diameter (open production interval)	8.5	inch
inner diameter (casing)	8.5	inch
casing roughness	1.38	milli-inch
injector well skin	-1	-
production well skin	-1	-

Two parameters are optimized per aquifer and location: well distance and pump pressure. The well distance is optimized in such a way that the maximum cooling of the production water after 50 years is 10%. This means that the difference between production water and return (injection) temperature after 50 years is at least 90% of the original temperature difference. The optimal pump pressure is obtained by minimizing the unit technical costs, with the constraint that the legally imposed maximum pressure as is not exceeded. To minimize the unit technical costs, the economic model needs to be run as well. The main output of the technical model is flow rate, temperature of the produced water and geothermal power. By running the model per aquifer and per 1x1 km grid cell, aquifer maps of the output properties are created.

2.5.2 Economic model

A discounted cash flow model is used to calculate the unit technical cost, meaning the net present value of all the costs including interest, inflation and tax, see Table 3. A simplified cost model is used, with depth dependent well costs in euros:

$$\boldsymbol{well\ capex = 375000 + 1150d + 0.3d^2} \quad [2]$$

where d is depth. The surface installation costs consist of a base amount and a variable part dependent on the power of the installation. The annual operation costs are dependent on the power of the installation and the amount of energy (heat) produced. The electricity costs to drive the pump are calculated separately using the optimized pump pressure. The economic lifetime of the geothermal installation is chosen to be 15 years, which is the duration of the SDE+ subsidy scheme. The SDE+ is an operating grant which compensates the difference between market price and renewable energy cost price.

The cost model is set-up in such a way that the overall costs (CAPEX and OPEX) match the cost analysis of the PBL Netherlands Environmental Assessment Agency, see PBL, 2019.

As mentioned before, the main uncertainty is assumed to be caused by the transmissivity. The techno-economic calculation is run for different probability values. The unit technical cost (UTC) maps of different probability values are used to construct economic potential maps for geothermal energy which contain the following classes:

- *Unknown*: UTC P10 > reference price
- *Indication*: UTC P10 < reference price
- *Moderate*: UTC P30 < reference price
- *Good*: UTC P50 < reference price

The reference price is 5.1 €ct/kWh, which corresponds to the SDE+ amount for geothermal energy. For doublets deeper than 4000 meters, another SDE+ category is valid where a price of 6.5 €ct/kWh is used.

Table 3: Economic parameters used in the batch discounted cashflow calculations

economic parameter	value	unit
economic lifetime	15	year
drilling time	2	year
annual load hours	6000	hour
well costs	depth dependent	M€
CAPEX base expense (excl. wells)	3	M€
CAPEX variable expenses (excl. wells)	300	€/kW
CAPEX contingency	15	%
annual OPEX per unit power	60	€/kW
annual OPEX per unit energy produced	0.19	€ct/kWh
electricity purchase price for operations	8	€ct/kWh
tax rate	25	%
interest on loan	5	%
inflation	2	%
required return on equity	7	%
debt ratio	80	%

2.5.3 Well stimulation and heat pump scenarios

The model described above yields the base case potential. Two additional scenarios have been calculated: the well stimulation scenario and the heat pump scenario.

Low aquifer permeabilities result in low flow rates. The flow rate can be improved by stimulating the well. Several well stimulation methods exist all of which have the goal to make the area around the well more permeable, i.e. they lower the well skin factor. For the well stimulation calculation scenario both the production well and the injection well are stimulated, resulting in a skin factor of -4 (compared to -1 in the base case). The cost of stimulating both wells is assumed to 0.5 million €.

Adding a heat pump to the installation will allow for more energy to be extracted from the water. A heat pump can be used to increase the temperature of the produced water or further decrease the temperature of the injection water. In practice the heat pump set-up will be highly variable depending on the temperature and flow rate of the produced water, and of the water needed in the heating process. For the heat pump scenario we used a generalized approach which lowers the return (injection) temperature from 30°C to 20°C with a fixed coefficient of performance of 5. The costs are dependent on the heat pump power, the initial costs are assumed to be 200 €/kW and the annual operational cost to be 20 €/kW. The electrical energy (to drive to heat pump) added to the water is excluded from the calculated power of the doublet, since this (grey) energy is not covered by the SDE+ subsidy. This energy is given a value of 2 €ct/kWh in the unit technical cost calculation, which is approximately the current heating cost using hydrocarbons.

2.5 'White spots' maps

A low geothermal energy potential can have two different causes: there are proven unfavorable subsurface conditions, or there is a lack of subsurface data. In the latter case the uncertainty is large, leading to a low P90 value of the calculated potential. In this case an exploration campaign could improve the potential. To distinguish between these two classes, i.e. to identify possible upside areas, 'white spots' maps were generated.

The white spots maps indicate subsurface data availability. A low value indicates poor data availability. The map was created by adding scores according to available subsurface data (old/new 2D seismic, 3D seismic, well data). This map is usually displayed in white with its value determining the transparency: the lower the value (i.e. few data), the 'whiter' (less transparent) the map. The areas with little data will stand out as white spots, hence the name.

3. RESULTS

An integrated stochastic geothermal resource assessment workflow has been constructed which results in regional geothermal potential maps of the Netherlands for direct-use. The main output maps per aquifer are listed in Table 4. These maps are available on www.thermogis.nl. The workflow and maps discussed here correspond to version 2.1 and will be regularly updated in the future.

The top depth, thickness, permeability, net-to-gross and transmissivity maps are created, incorporating geological insight through geological and geo-statistical modelling. For thickness and permeability uncertainty is taken into account, resulting in P90, P50 and P10 probability maps, see Figure 4 as an example for the permeability of the Upper Rotliegend aquifer. The temperature maps are extracted from the 3D subsurface temperature model. A horizonal slice at 2 km depth through the 3D temperature model is displayed in Figure 7, with the misfits between the modelled and measured temperatures displayed as colored dots. The flow rate and power P90, P50 and P10 probability maps result from the geostatistical technical calculation, see Figure 5 as an example for the expected geothermal power maps for the Upper Rotliegend aquifer. The economic model with subsequent unit technical cost cut-offs yields the economic potential. For some map types different probability and scenario versions exist, indicated with a superscript 'P' and 'S', respectively, in Table 4.

Aside from the aquifer maps, additional overview maps are created by adding the potential for all stacked aquifers apart from the Carboniferous Limestone groups (see Table 1). This way, general geothermal potential maps are constructed, see Figure 6. This figure also displays the potential maps for the well stimulation and heat pump scenarios, both of which show a larger geothermal potential than the base case. The well stimulation will especially improve aquifers with a lower permeability, generally the deeper aquifers. While the heat pump will especially benefit shallow aquifers that generally have higher flow rates but lower production water temperatures.

An overview map has also been created for the previously discussed white spots map. Figure 8 displays this map overlaid on the base case geothermal overview potential map.

Table 4: Main ThermoGIS output maps per aquifer. P: probability maps, S: alternative scenario maps for well stimulation and heat pump.

map	unit	description
top depth	m	depth of the top of the aquifer
thickness p	m	gross thickness of the aquifer
permeability p	mD	permeability of the net aquifer
net-to-gross	-	net-to-gross ratio of the aquifer
transmissivity p	Dm	product of thickness, net-to-gross and permeability
temperature	°C	temperature at mid-aquifer depth
flow rate p,s	m³/hr	production and injection flow rate
power p,s	MWth	geothermal power of the doublet
heat in place	GJ/m²	initial heat content of the aquifer
potential recoverable heat	GJ/m²	heat that could theoretically be extracted without technical or economic constraints
technical potential s	-	technical potential based on subsurface conditions and doublet parameters
economic potential s	-	potential constraint by technical and economic limitations
'white spots'	-	transparency overlay indicating data availability

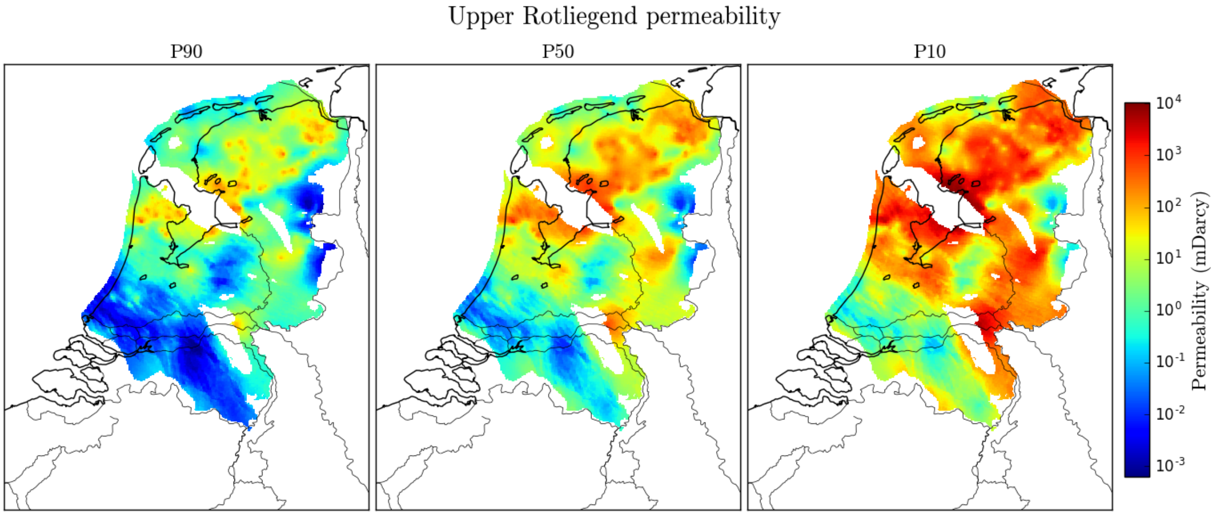

Figure 4: Upper Rotliegend permeability maps in millidarcy for different probability levels: P90, P50 and P10.

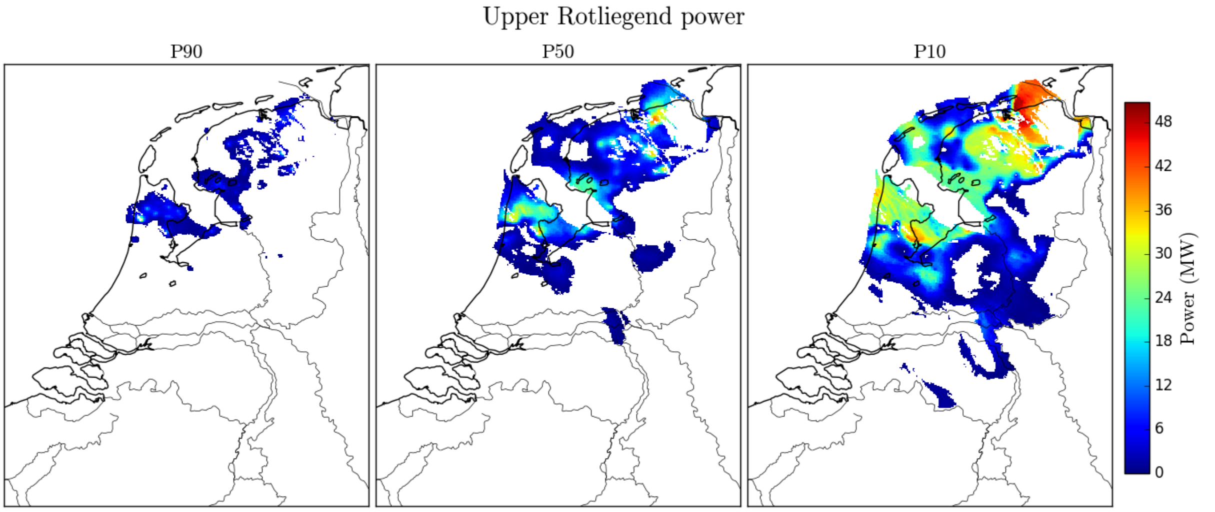

Figure 5: Upper Rotliegend power maps in MW for different probability levels: P90, P50 and P10, areas with hydrocarbon accumulations are excluded.

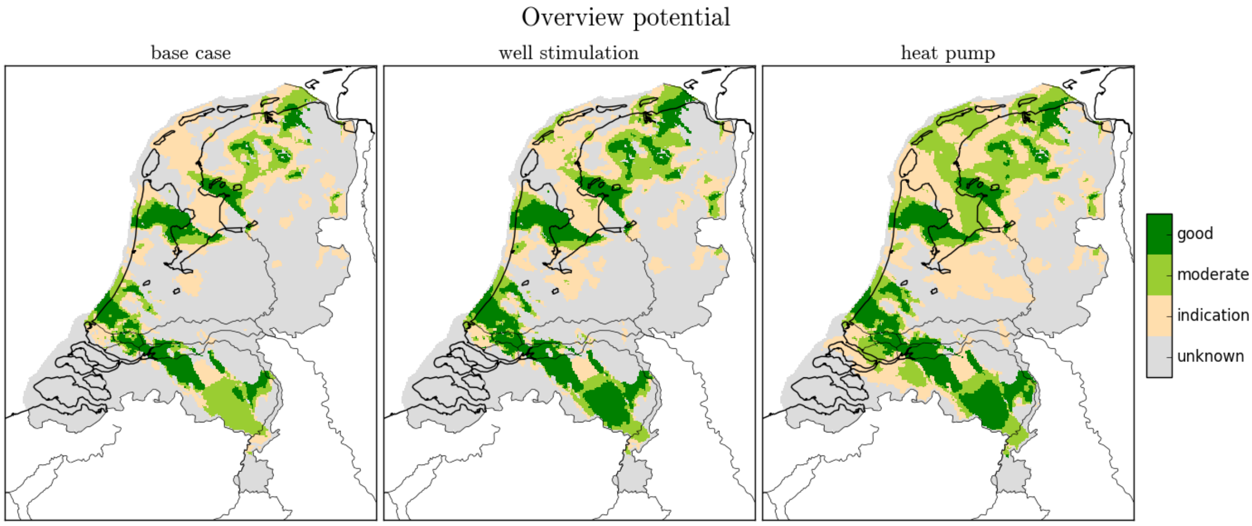

Figure 6: Overview (all aquifers combined) geothermal potential for the base case, well stimulation and heat pump scenarios

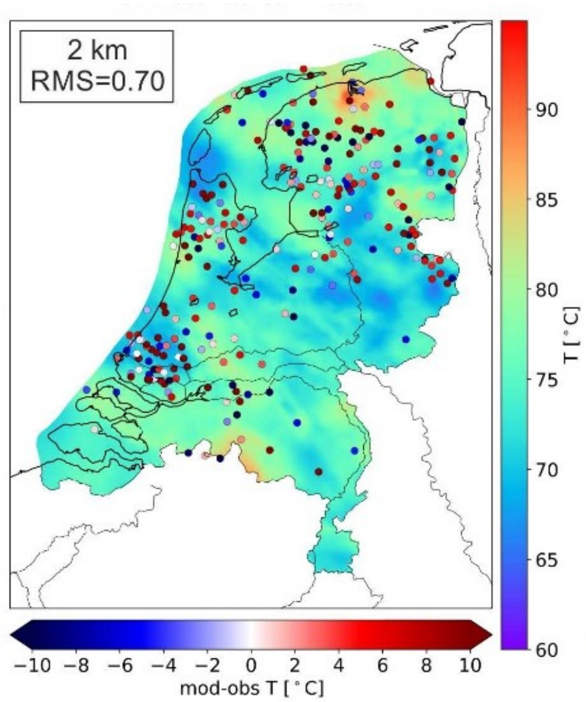

Figure 7: Temperature map at 2 km depth from the data assimilated 3D temperature model. The dots represent the misfit between modeled temperature and measurements within a ±200m interval, from Békési et al. (2019).

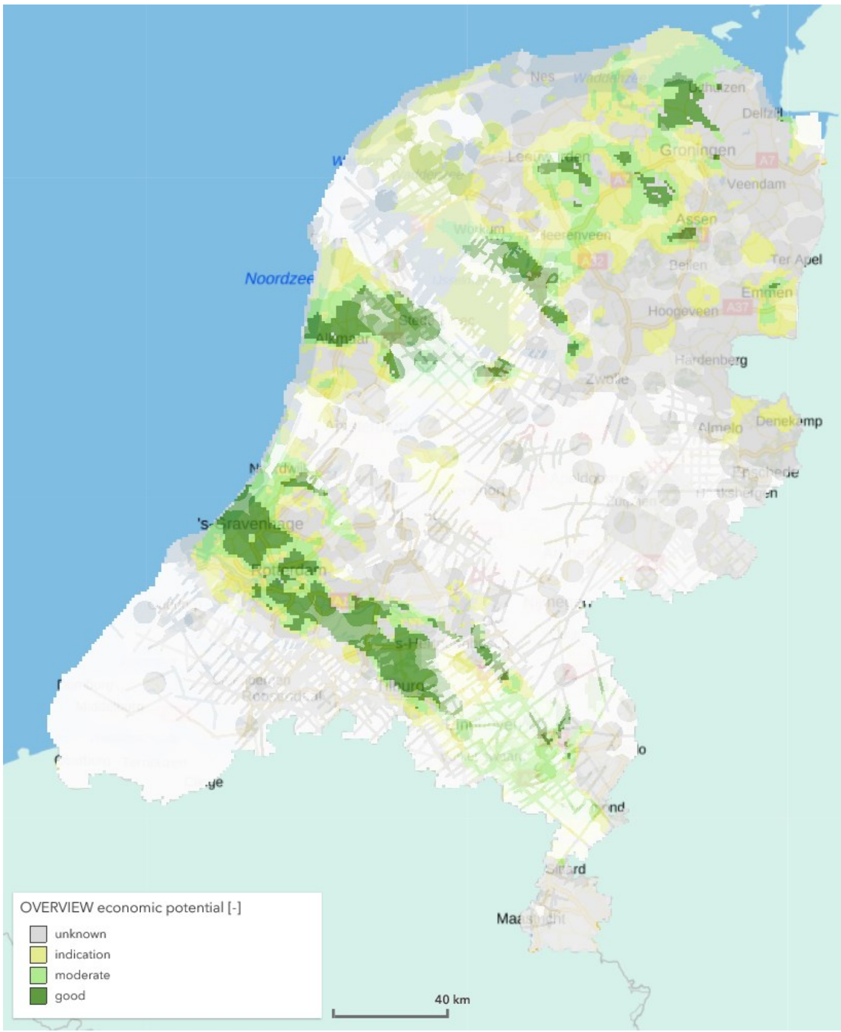

Figure 8: Overview geothermal potential overlain with the ‘white spots’ map.

4. DISCUSSION

The ThermoGIS method is an integrated stochastic regional geothermal potential calculation using a generalized workflow. For a possible specific geothermal development, a more in-depth local geological and economic feasibility study must be performed. The geothermal potential is calculated for direct-use of heat application. Electricity generation using geothermal energy is not taken into account since the expected temperatures for the analyzed aquifers are not high enough.

The geothermal potential has been calculated for a selection of aquifers which are known to have sufficiently high flow properties from available subsurface data (Table 1). There could be other interesting geothermal aquifers, especially in ‘white spot’ areas and deeper sections (>4 km) than currently sampled by well data. These ‘white spot’ areas and deeper sections are interesting targets for exploration. With the arrival of improved heat pumps and better integration with the geothermal system, shallower geothermal energy (500-1500m) could become viable as well.

Technological advances could also increase the geothermal potential. Drilling technology advances, for instance, could reduce drilling time, thereby decreasing the costs. Future heat pumps could have a higher efficiency and more effective well stimulation measures could become available.

The economic analysis was performed using Q1 2019 costs, subsidy scheme and other economic parameters. Changes in these parameters will affect the geothermal potential maps. The Dutch government is looking into ways of stimulating the energy transition away from hydrocarbons. This could lead to improved and additional subsidy schemes.

As mentioned previously, the maps are available on www.thermogis.nl. Regular updates are planned to incorporate new data, insights, technologies and economic circumstances, including subsidy schemes and taxes. The resulting maps can be used to calculate overall geothermal resources numbers for the Netherlands (Mijnlieff et al. (2020)). Another interesting future use of the maps could be to calculate the matched geothermal potential by incorporating surface heat demand data, see Figure 8.

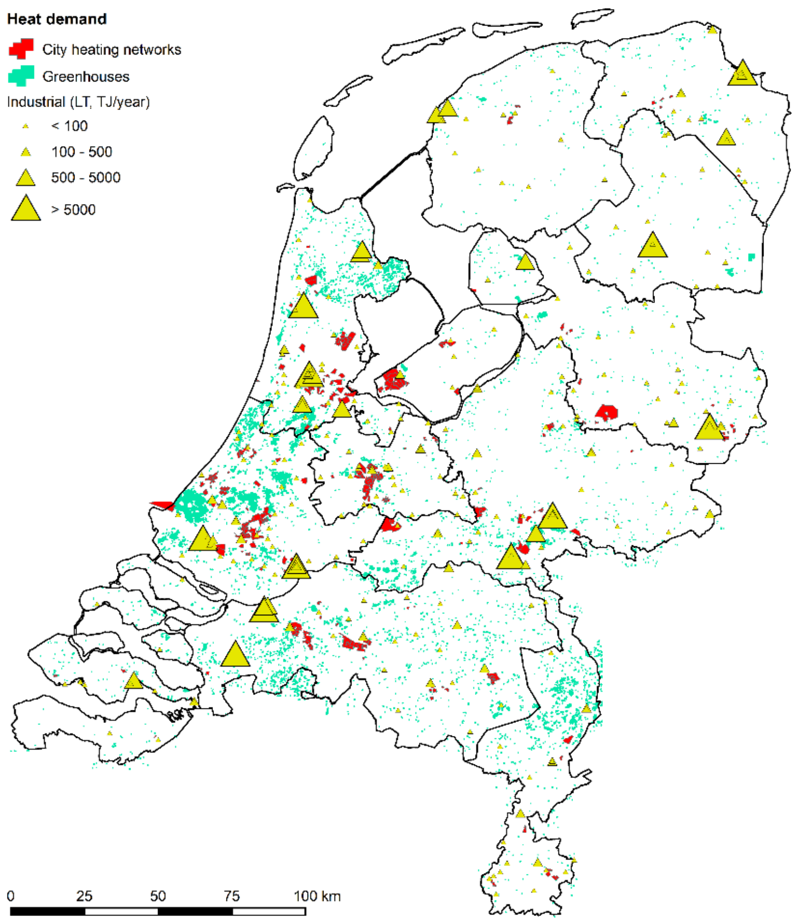

Figure 8: Heat demand map for the Netherlands from RVO (2019).

5. CONCLUSION

The ThermoGIS workflow models the geothermal potential for the Netherlands, using the available subsurface data from oil and gas experience. Multiple aquifers exist with a good geothermal potential at different depths and temperatures. Large parts of the Netherlands are suitable for geothermal development. Adding well stimulation or a heat pump will increase this area.

The resulting maps support companies and the government to develop geothermal energy. ThermoGIS can serve as a quick-start for geothermal projects. Since it is a regional evaluation, a more detailed local study is necessary before future development.

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