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Review

Unlocking Geothermal Energy: A Thorough Literature Review of Lithuanian Geothermal Complexes and Their Production Potential

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Abstract: Lithuania is located on the East of Baltic sedimentary basin and has a geothermal anomaly situated in the southwestern region of the country. There are two primary geothermal complexes within the anomaly, composed of Cambrian and Devonian aquifers. The Cambrian formation is composed of sandstones that have a reservoir temperature reaching up to 96 °C (depth > 2000 m). The Devonian aquifer is composed of unconsolidated sands of Parnu–Kemeri and has a reservoir temperature of up to 46 °C (depth > 1000 m). Historically, both formations have been investigated for geothermal energy production. In this article, we present a detailed literature review of the geothermal work carried out on both formations, including past, present, and some possible future studies. The study presented in this paper highlights the key findings of previous research work, summarizes the research gaps, and then elaborates on the possible applications of emerging technologies to bridge the research gaps and improve our understanding of geothermal complexes in Lithuania. Although it is not the main aim of this article, this article also touches upon the important need to develop 2D/3D numerical models, to quantify uncertainties, in the evaluation of the geothermal potential in Lithuania for commercial development. This study also highlights possibilities of extending geothermal development to depleted hydrocarbon reservoirs through repurposing the high-water-production wells. Moreover, from the literature review, it can be concluded that the Lithuanian geothermal aquifers are hyper-saline in nature and temperature changes lead to the deposition of salts both upstream and downstream of the reservoir. Therefore, there is a need for developing multiphysics thermo-mechanical–chemical (THMC) models for evaluation of reservoir behavior. The literature also describes the potential use and development of the THMC model as a part of future work that must be carried out.

Keywords: Cambrian; Devonian; geothermal; Lithuania; reservoirs; depleted reservoirs; aquifers; screening; numerical modeling

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1. Introduction

The Earth is rich in diverse natural resources, comprising both renewable and non-renewable forms. Non-renewable resources such as coal, oil, and gas significantly contribute to global climate change. The extraction and production of fossil fuels, petrochemicals, and other gases have led to environmental pollution, elevating the Earth's temperature due to the predominant emissions of carbon dioxide and methane. To address the imperative of achieving net-zero CO_2 emissions and mitigating carbon footprints, there has been a notable surge in the utilization of renewable energy sources, like geothermal, wind, solar, tidal, hydropower, biomass, and geological storage of H_2 and CO_2 in the subsurface.

Geothermal energy, a distinctive form of renewable energy, derives from the Earth's core, tapping into the heat generated during the planet's original formation and the subsequent radioactive decay of minerals. This thermal energy is stored in rocks and fluids deep within the Earth. Geothermal energy has become increasingly popular in both developed and developing countries, offering advantages such as cost-effective development, reliability, sustainability, and environmental friendliness. While historically limited to regions near tectonic plate boundaries, recent technological advancements have significantly broadened the range and size of viable geothermal resources. This expansion has paved the way for diverse applications, including home heating, and holds the potential for widespread utilization.

Although geothermal wells also release greenhouse gases that are naturally trapped deep within the Earth, these emissions are considerably lower per unit of energy compared to those generated by fossil fuels. In this paper, we conduct an extensive literature review with the aim of evaluating geothermal potential in Lithuania. The literature review provides insights into the past and present studies while exploring future scenarios. The examination encompasses the multifaceted aspects of geothermal energy, emphasizing its role in the global shift toward sustainable and environmentally conscious energy practices.

This paper is organized as follows: a brief country overview is first presented. Next, details of the literature used are presented with key findings. Research gaps identified from the literature review are presented next, followed by discussion on the need for the use of simulation models to study Lithuania's geothermal potential and how the use of new technology can aid in this evaluation. Finally, this paper presents an approach to a way forward and conclusions.

Brief Country Overview: Geothermal Aspects in Lithuania

Lithuania lies in the eastern part of the Baltic sedimentary basin and on the western margin of the Early Precambrian consolidation. It is in central Europe and share borders with Latvia in the north, Belarus in the east and south, Poland and the Kaliningrad enclave (Russia) in the southwest, and the Baltic Sea in the west. The total area of the country is about 65,300 km^2. The average mean temperature ranges between 5 °C and 9 °C; therefore, houses are to be heated from October to April. The net energy consumption of Lithuania has been reported as 50.8 GJ per capita (13 MW-h) and therefore has more potential for geothermal resources [1]. Further details regarding energy consumption and forecasts are provided in Table 1.

Table 1. Consumption and prognosis for renewable energy resources for Lithuania, 1000 ton-eq [2].

Sr. No	Type of Sources	Year		
		2006	**2010**	**2025**
1	Firewood and wood	728.2	795	1015
2	Agriculture waste	1.7	25	120
3	Biogas	2	10	20
4	Sprout.		20	70
5	Wind	1.2	35	90
6	Hydro	34.2	40	45
7	Biofuel	20.9	115	450
8	Municipal waste		25	120
9	Geothermal and solar	1.7	10	45
10	Other	0.1	12	80
	Total	790	1090	2055
	% in Primary energy balance	9.2	12.6	19.6

Out of the total gross energy production, the renewable and indigenous resources contribute 11.4% as depicted in Figure 1, but the European Union set the goal for Lithuanian geothermal contribution to 25% by 2020, which is related to goals to reduce greenhouse gas emissions [2]. Many authors have highlighted the significant geothermal anomaly in the western part of Lithuania [2–6]. The heat flow in this western region is notably more irregular and intense compared to the eastern region. This disparity is attributed to Lithuania's substantial geothermal resources concentrated in the western part. Consequently, the western region is home to the Klaipeda Geothermal Plant (KGDP), representing the sole geothermal facility in this area. Although initially successful, the geothermal plant has ceased operations as of 2017 due to operational and financial constraints [5].

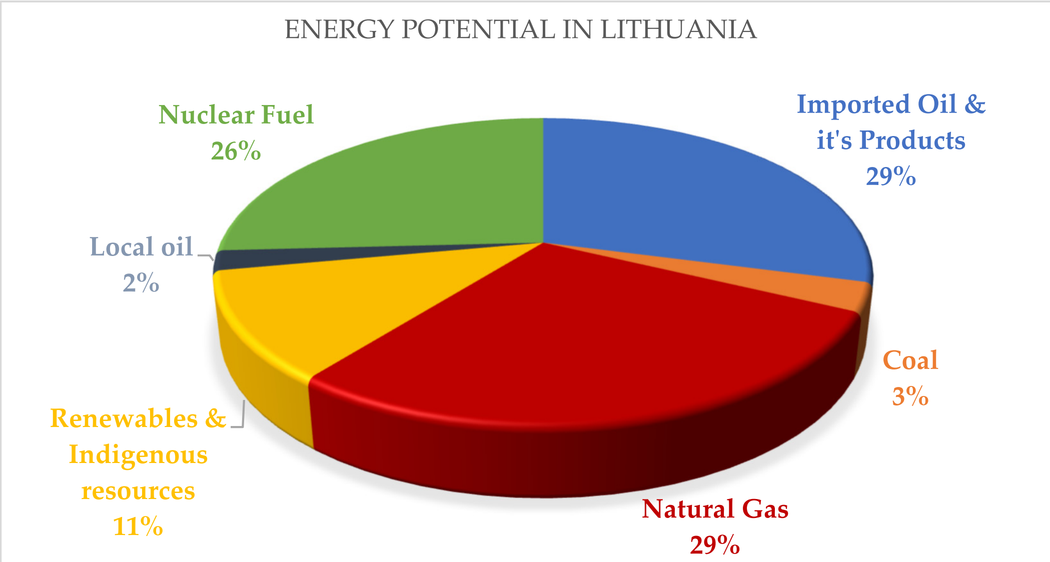

Figure 1. Energy production in Lithuania [2].

2. Review of Geothermal Studies in Lithuania

In this section, we present a high-level summary of the various research publications in geothermal energy exploration carried out in Lithuania. A total of 22 research articles are reviewed and a brief summary of their key findings is presented in Table 2. At the end, a high-level summary is also presented.

Table 2. Table showing list of papers, authors, and key findings of the geothermal studies carried out in Lithuania.

Title	Authors	Key Findings
Geothermal Field of the Vydmantai-1 Borehole Within the Baltic Heat Flow Anomaly [7]	P. Suveizdis et al., 1997.	It is the first Lithuanian geothermal publication, revealing a heat flow density of 52 to 55 mW/m^2 in the specified interval and detailing drilling, completion, thermal conductivity data for sedimentary cover, and vertical variation in heat flow density in both sedimentary and crystalline basement.
Geothermal Potential of Lithuania and Outlook for its Utilization [1]	Povilas Suveizdis et al., 2000.	The findings encompass the presentation of Lithuania's geologic and tectonic situation, emphasizing the potential for renewable sources, including seismic, oil, and gas opportunities, and geothermal exploration surveys. The identification of geothermal resources is concentrated in hot dry rocks (HDRs) and three aquitards in the sedimentary basin, and there is a proposal to utilize the variable temperature in the upper zone (Quaternary) for heat extraction and the establishment of a KGDP plant.
Klaipeda Geothermal Demonstration Project [3]	Bronius Radeckas et al., 2000.	The key finding describes the KGDP plant, comprising two injectors and two producers drilled and completed at the same depth, with the conclusion that this technology would reduce greenhouse gas emissions, noting the plant's operation in 2000.
A Reservoir Model And Production Capacity Estimate For Cambrian Geothermal Reservoir In Kretinga, Lithuania [8]	Vytautas Puronas, 2002.	The key finding includes estimating the potential of the Cambrian geothermal layer in a depleted oil and gas field in Kretinga, West Lithuania, utilizing data from seven drilled wells, developing a 3D numerical model of the Kretinga geothermal reservoir, and emphasizing the importance of a detailed numerical model with variations in temperature and pressure for gaining deeper insights into geothermal potential.
Geothermal Potential and First Achievements of its Utilization in Lithuania [4]	Feliksas Zinevicius et al., 2005.	The key finding describes the operational challenges and declining injectivity reported at the KGDP plant, despite efforts to clean both injectors' bore-holes, resulting in failure to reach the desired injection capacity.

Table 2. *Cont.*

Title	Authors	Key Findings
Lithuania—Geothermal Energy Country Update [2]	Feliksas Zinevicius, and Saulius Sliaupa, 2010.	Key findings encompass the creation of a Lithuanian geothermal map, identification of heat capacity using duplet wells, and recommendations for international collaboration among geothermal experts to tackle challenges like injection, corrosion, and microbiological activity to reverse declining injectivity.
Computer Models, Used for Klaipeda Geothermal Plant Operation Failures Analyse [9]	Antanas Algirdas Klimas et al., 2010.	The authors' key findings include the description of KGDP plant failure, reducing injectivity due to the precipitation of salts, minerals, and ions, which clog filters and aquifer pores; their conclusion is that preventing oxygen entry surpasses Fe-oxides, hydroxides, and sulfur scales; the modeling study indicates that injecting spent GTW is not feasible and that fresh groundwater injection is not very effective; and the effectiveness of soft acidification helps in mitigating scale problems that lead to declining injectivity.
The Geoenvironmental Impact of Klaipėda Geothermal Plant [10]	Algirdas Zuzevičius et al., 2011.	Key findings involve the creation of mathematical models for hydrodynamic, hydro-chemical, and geothermal processes using geological and hydrogeological data. The results suggest ample thermal energy resources for KDGP operation at a 21 MW geothermal capacity over 50 years, with well spacing of 200 to 500 m, while noting the potential for groundwater mixing to impact ferrous minerals and the irreversible cooling of the Viešvilė aquifer within the designated zone.
Approach to develop a soft stimulation concept to overcome formation damage—A case study at Klaipeda, Lithuania [11]	Maren Brehme et al., 2017.	The author's key findings involve investigating well injectivity enhancement for KGDP through a feedback adjustment procedure to tackle formation damage, concluding that clogging of the filter screen and reduction in reservoir pores result from precipitation of salts, minerals, corrosive particles, and biofilm formation, with suggested remedies to address these issues.
Injection-Triggered Occlusion of Flow Pathways in Geothermal Operations [12]	Maren Brehme et al., 2018.	The authors categorized clogging processes into three sections—physical, chemical, and biological processes—and concluded that each of these processes has an individual adverse impact, predominantly related to the formation; their conclusions were drawn from laboratory investigations, analysis of fluid and rock samples, and operational data, including numerical modeling, revealing that the historical exponential decline of injectors is attributed to the directional nature of the permeability structure.
Report on a field scale RJD stimulation for the Klaipeda site [13]	Sigitas Petrauskas. et al., 2019.	The article introduces radial jet technology stimulation techniques to enhance the injectivity of the KGDP geothermal plant's injector, particularly applied to injector 1I and other more productive zones; however, the key finding indicates that, despite numerous efforts, the post-stimulation injectivity rate remained small and temporary, with an overall injection rate increase of about 39% after two years, likely attributed to the skin effect.
Geothermal Energy Use, Country Update for Lithuania [14]	Saulius Šliaupa et al., 2019.	The authors explore the causes of KGDP plant failure, underscore the potential of the Cambrian and Lower Devonian aquifer layers, and recommend repurposing the plant for SPA treatment, agricultural farming, and balneology, emphasizing the competitive advantages of shallow geothermal energy.
A Review of the Hydrochemistry of a Deep Sedimentary Aquifer and Its Consequences for Geothermal Operation: Klaipeda, Lithuania [15]	Maren Brehme et al., 2019.	In this article, the authors detail the hyper-saline composition of geothermal aquifers and observe a slight declining trend in salinity with an increase in bicarbonate composition; their findings conclude that multiple attempts to reverse falling injectivity have been unsuccessful, attributing calcium polyphosphonate dosing to pore throat clogging and finding that temporary back pumping from the same wells helps in pore enlargement and flow occlusion release.
Geothermal development in Lithuania [6]	Feliksas Zinevicius et al., 2003.	The key finding indicates that declining injectivity is linked to unexplored injection capacities post well drilling, a lack of microbiological investigations regarding H_2S and H_2 contents in wellheads, and insufficient measures to maintain constant pressure. Despite reduced precipitation of gypsum, clay, and ferrum oxides in injector 4I and 1I results, the injectors were unable to reach their full capacity of 700 m^3/h.
Death by Injection: Reopening the Klaipėda Geothermal Cold Case [5]	Frédéric Guinot, and Serge Marnat, 2021.	The author's key finding results in a comprehensive analysis of operational failures in the KGDP plant, utilizing petrophysical parameters, production logs, and injection/production data, pinpointing major flaws in the injector well design. Based on these conclusions, they propose remedial actions to revive the Klaipeda geothermal project and express hope that this work will serve as a foundation for best practices in drilling and completing future wells in clastic reservoir rock.
Reinjection in Geothermal Fields: A Worldwide Review Update [16]	Alexandre Rivera Diaz et al., 2015.	The authors' findings stress the experimental and site-specific nature of re-injection design, highlighting the importance of early planning in field development, advocating for flexibility, and emphasizing the need for optimal design to balance reservoir pressure, prevent early breakthrough of cold re-injected fluid, and manage thermal effects.

Table 2. *Cont.*

Title	Authors	Key Findings
Optimization of well-doublet placement in geothermal reservoirs using numerical simulation and economic analysis [17]	Yanlong Kong et al., 2017.	The authors' key finding, derived from numerical simulations, concludes that the optimal distance between well doublets is 400 m, emphasizing the importance of deeper injection methods in field development; additionally, economic analysis suggests that the optimal distance is more reliant on the ratio of heat price over electricity than on individual parameters for heat or electricity prices.
Well placement optimization for geothermal reservoir under subsurface uncertainty [18]	R. Schulze-Riegert et al., 2022.	The authors' key finding reveals that uncertainties in the discrete fracture network creation process are strongly influenced by parameter absolute permeability, which, in turn, contributes to model validation, identification of hot spots for well location, and the management of classical decision tree analysis.
Geothermal Rapid Screening [19]	A. Parent et al., 2022.	The author's work involves creating a geothermal rapid screening (GRS) 1D machine learning tool to establish the relationship between temperature and depth based on lithologies from existing wells; their findings encompass assessing the impact of subsurface uncertainty in model parameters like temperature, heat, flow, porosity, permeability, and thermal conductivity, determining risks associated with converting existing water, oil, or gas wells into geothermal well candidates for further investigations.
Unsupervised AI Workflow to Evaluate CO_2 Storage and Geothermal Potential Over a Giant Mature Gas Field [20]	Laugier B., and Aming A., 2022.	The authors' findings involve the development of an unsupervised artificial-intelligence-based genetic algorithm that processes seismic data unbiasedly to assess CO_2 storage and geothermal potential. This algorithm automatically generates waveform suites, attributes, and characterizations of surfaces and faults, facilitating the construction of stratigraphic/structural domain and seismic facies maps throughout the entire Groningen area.
Modeling and Optimization of Shallow Geothermal Heat Storage [21]	Ø. Klemetsdal et al., 2022.	The author's findings suggest that discrete fracture modeling (DFM) is suitable for wellbore modeling, and adjoint-based optimization is applicable for optimal control and parameter tuning of geothermal plants. They also indicate that explicit fracture modeling works well when rock fracture density is low, whereas if the density is high, adequately modeling can be achieved using upscaled rock parameters.
Uncertainty quantification and optimization method applied to time-continuous geothermal energy extraction [22]	Hussein Hoteit et al., 2023.	The author's work introduces a novel method for estimating thermal recovery and produced-enthalpy rates, coupled with uncertainty quantification and optimization; their key finding indicates that thermal conductivity is insignificant to the re-injection process, with heat transfer dominated by convection, and that the efficiency of thermal recovery and enthalpy production is significantly influenced by permeability, rate, porosity, and well spacing. The proposed approach allows for quick screening and optimization of new field developments when detailed data are unavailable, with the option for numerical simulations when sufficient data are present.

Summary of Key Findings

It can be concluded from the literature review presented above that, in Lithuania, there are numerous geothermal reservoirs in the western part of the country situated on the three geothermal aquifer zones, namely Upper-Middle Devonian (D_1), Middle-Lower Devonian ($D_{2–3}$), and Cambrian strata, based on the reservoir properties. There are three hydro-geothermal complexes in the sedimentary cover of Western Lithuania: the Cambrian (140 m), Middle-Lower Devonian (400 m), and Upper-Middle Devonian (200 m) [6]. Figure 2 depicts the geological cross-section of the Western Lithuanian territory.

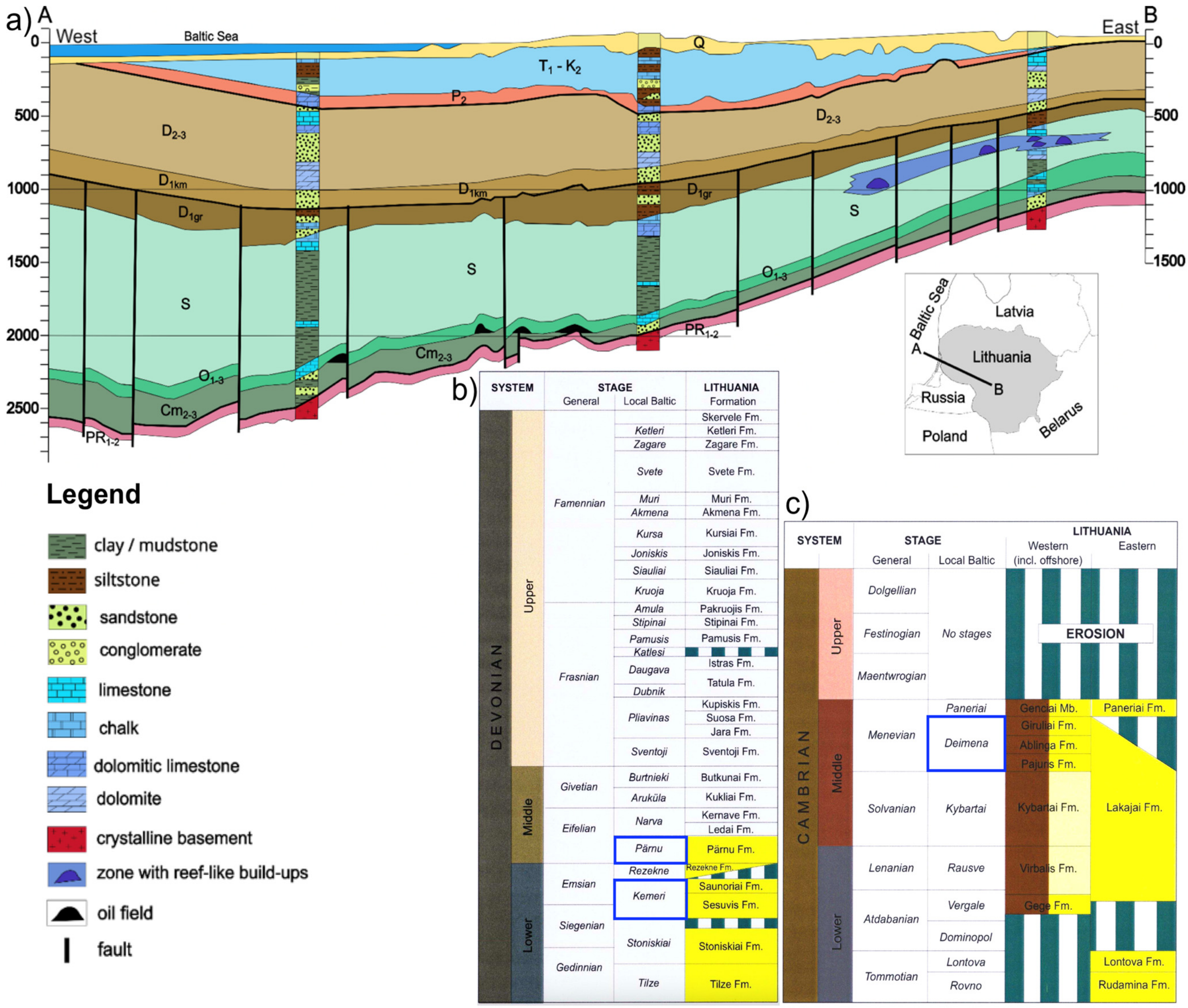

Figure 2. (**a**) Generalized geological cross-section throughout Lithuanian territory (A, B profile as marked on the Lithuanian map) with Devonian (D) and Cambrian aquifers (cm). (**b**,**c**) Stratigraphic columns of Devonian and Cambrian successions; modified after [23]. Investigated intervals are marked in blue.

Table 3 provides an overview of the historical progression of geothermal development in Lithuania [24]. The exploration of geothermal resources in Lithuania commenced between 1987 and 1989, culminating in the drilling of the Vydmantai-1 deep exploration well. During this drilling, a comprehensive set of 100 hard rock samples and 12 bedrock samples were collected, and their thermophysical properties were meticulously estimated. The borehole traversed the entire sedimentary basin, reaching the Cambrian region from depths of 2122 m to 2564 m [7]. Throughout the drilling process, various petrophysical logs, grain size analyses, mineralogical assessments, filtration coefficient evaluations for the Devonian layer, crack examinations, groundwater chemistry analyses, microelement content assessments, and thermophysical property determinations were conducted. These invaluable data sets have been extensively utilized by multiple researchers for subsequent studies [1–6,8,9,11,13–15,19,20]. Between 1992 and 1994, the Danish government sponsored the 'Baltic Geothermal Energy Project', which investigated the geothermal potential in Lithuania and Latvia. This initiative scrutinized all regional aquifers within the Devonian and Cambrian strata, considering the considering energy needs and geothermal potentials. In 1993, the second well, Vydmantai-2, was drilled and completed; however, due to financial constraints, the well was eventually shut in. From 1992 to 1999, a total of 19 exploration wells were drilled for assessment purposes. During 1995–1996, site selection and geothermal potential calculations were conducted, leading to the choice of Klaipeda as a pilot location.

Table 3. Historic overview of geothermal energy in Lithuania.

Geothermal Historic Overview (Lithuania)	
Year	**Event**
1989	First Geothermal Well—Vydmantai-1
1992	Baltic Geothermal Project Initiated
1993	Second Geothermal Well—Vydmantai-2
1993–1999	Further Geothermal Exploration Well Drilled (19)
1995–1996	KGDP Conceptualized—Devonian Waters
2000	KGDP—Start Operation (700 m^3/h @ 40 °C)
2002–2010	KGDP Operational Issues (re-injection)
2010–2016	Injection Remediations Work—Proved Unsuccessful
2017	Financial Issues and Plant Ceased Operation

In the year 2000, the Klaipeda Geothermal Demonstration Plant (KGDP) was constructed, marking the first project financed by the World Bank that transferred geothermal energy to the district heating system using heat pump technology. The KGDP plant drew geothermal water from the Lower Devonian strata at a temperature of 40 °C (estimated at 42 °C) at a vertical depth of 1000 m [5]. With a total thermal capacity of 41 MW (18 MW geothermal and 23 MW from boilers), the KGDP plant extracted approximately 215,000 MW-h of heat in 2003. Initially, only injector 1I was drilled, but it proved insufficient for injecting the desired 700 m^3/h of geothermal water. Consequently, a new injector, 4I, was drilled. Presently, the KGDP plant features two production wells (KGDP-2P, KGDP-3P) and two injection wells (KGDP-1I, KGDP-4I), all identical in design and completed at depths of 1128 to 1228 m.

In 2009, a proactive effort to counteract declining injectivity led to the decision to sidetrack well KGDP-1I. The sidetracking initiative commenced at 897 m, creating a slanted section with a 3° to 5° deviation from the vertical, reaching depths of 1116 m (all depths measured from ground level). Unfortunately, the sidetracking of KGDP-1I resulted in a disheartening reduction in injectivity, decreasing from 2.3 to 1.7 $m^3/h/bar$. Numerous authors have highlighted this injectivity decline, prompting various chemical stimulation techniques, including radial jet drilling (RJD), which was implemented in 2014. Subsequently, in December 2014, a total of 12 laterals were jetted into KGDP-1I, with 9 reaching 40 m, 2 reaching 35 m, and 1 reaching only 28 m. Three months after these operations, tests indicated a positive but modest improvement, with injectivity increasing by only 14%. Following this, a series of acid injections were carried out, resulting in a 39% overall improvement in injectivity, although the enhancement remained marginal.

The water salinity in Cambrian varies from west to east, i.e., 0.5 g/L (977 kg/m^3) in the southernmost or east region to 200 g/L (1129 kg/m^3) in the west, while the Lower Devonian formation water possesses variable salinity of 0.2–0.5 g/L (993 kg/m^3) in the east to 40–90 g/L (1060 kg/m^3) in the west [2]. Moreover, the KGDP plant, which is situated on the Devonian strata, has a mineral content with more than 96% NaCl and $CaCl_2$ with a pH value of 6.3. Furthermore, one liter of geothermal water contains 160 mL of dissolved gas, which is N_2, i.e., approximately 94%. This geothermal water is pumped out by submersible pumps with a flow rate of 300 to 400 m^3/h and a pressure head of 245 m [3,9].

Comparing this to the salinity of Baltic Sea water, which is 35 g/L, it is evident that the formation water is hyper-saline in nature [15]. Consequently, re-injection of this produced water at a lowered temperature leads to the precipitation of minerals. In 2002, during the wellbore cleaning process of both the injectors, the residues of gypsum, clay, and ferrum oxides were pumped out. However, the subsequent test after the clean-up did not show a positive response in terms of increased injection and ability to reach the full capacity of 700 m^3/h [4].

From the inception of the KGDP plant in 2002 until 2010, the facility encountered numerous operational challenges attributed to the precipitation of gypsum and other minerals in both upstream and downstream lines. Additionally, the plant faced issues related to material corrosion, deposition, and the degasification of N_2 in the operational lines. Despite the marginal gains achieved for a limited duration, the remedy's impact was minimal and ultimately proved unsuccessful. Since 2017, financial difficulties have plagued the plant, leading to its cessation of operations.

3. Research Gaps

In this section, we summarize the research and data gaps, which exist to further improve our understanding of Lithuanian geothermal system. The exploration, development, and production of geothermal resources incorporate techniques from both the mining and oil/gas industries. Geothermal systems share geological characteristics with metal ore deposits, positioning them as modern counterparts to ore-forming systems. Consequently, the exploration of geothermal resources leans heavily on mining industry techniques. However, the development and production of geothermal resources, involving hot fluids, draw from the methods used in the oil/gas industry, with necessary modifications. Several factors distinguish geothermal resource management:

High Temperatures and Flow Rates: Commercial-scale geothermal production requires significantly higher temperatures and flow rates for economic viability.

Produced Water Disposal: The disposal of produced water is crucial, making re-injection a vital consideration, an aspect often overlooked in past geothermal exploration and development.

Role of Water Chemistry: Geothermal complexes deal with a single phase, either formation water or brine, rich in mineral salts. Water chemistry, particularly in hot springs and fumaroles, is a key tool in geothermal exploration.

Presence of Gases: The presence of gases in the geothermal reservoirs can affect the overall geothermal resources and their utilization. These gases can be in dissolved form or as free gas. Therefore, understanding the behavior of these gases is crucial for resource extraction, operational safety, and less environment impact.

Solubility of Minerals: The solubility of minerals is temperature-dependent, with the kinetic rate of rock–water interactions playing a crucial role. The geochemistry of thermal aquifers is widely used for estimating subsurface temperatures before drilling. This aspect could also be better managed using reactive transport modeling approaches such as using 3D reservoir modeling software like TOUGHREACT [25] and incorporating learning from reference [26].

Geophysical or Seismic Interpretation: Interpretation in geothermal fields can be complicated by factors such as rock type and complex geologic structures. Geophysical measurements or seismic interpretation aid in identifying permeable structures containing high-temperature water or steam and assessing the potential heat extraction from the ground within a specified timeframe. Once a field is operational, geophysical measurements can assist in identifying suitable locations for additional production and injection wells, understanding the intricacies of permeability structures, and providing constraints for reservoir models used in geothermal field management. During this reservoir development phase, the main exploration objectives revolve around co-locating heat, fluid, and permeability. Thanks to advancements in geophysical techniques and emerging technologies, the process has become automated, accelerating interpretation steps with higher resolution, thereby resolving complex issues, uncertainties, or faults associated within geothermal reservoirs.

Measurement of Heat Transfer: Subsurface temperatures in aquifers can be sensed during drilling exploratory wells, and the combined temperature gradient and thermal conductivity of rocks help to determine vertical heat transport.

Estimation from Physical Properties: Subsurface temperatures can be estimated from physical properties of rock masses, including density, seismic, electrical, and mechanical properties.

Borehole Logging: While borehole logging systems are less applied to geothermal aquifers due to high water flow, high-temperature logging can mitigate circulation loss issues.

Reservoir Engineering: Geothermal reservoir engineering mirrors petroleum engineering and involves heat and mass transfer, vaporization of water, and conventional play features.

Utilizing Depleted Hydrocarbon Reservoirs: Depleted hydrocarbon reservoirs are attractive for geothermal potential, stemming from the same origin of high-temperature water. Converting high-water-cut wells for geothermal use reduces overall drilling and field development costs.

The lack of the above data introduces many uncertainties in the field evaluation. These data are not available for most geothermal complexes, which is a shortfall in our literature study. Furthermore, temperature gradient [2,8,10,11] and thermal conductivity [7] measurement of rocks for the Lithuanian geothermal complex field can be obtained from the above literature review. The detailed gamma ray log before and after injection can be obtained from reference [5].

Utilization of Lithuanian hydrocarbon reservoirs for geothermal energy production has been investigated in the screening study presented in [27], where series of numerical simulation models are used for evaluating the geothermal energy production potential of a number of Cambrian reservoir sites. The modeling work presented in [27] only evaluated sites using an injector–producer pair; additional work can also be carried out where existing oil production wells, which are now producing 100% water, could be horizontally extended to increase their production. Such ideas need to be investigated using reservoir models, a work which we will consider in future publications. In a similar manner to the screening study presented in [27], a screening study targeting Devonian geothermal complexes is also required.

4. Need for Simulation Studies

The subsurface investigation delves into the intricate nature of reservoirs, involving various processes such as geometry, hydraulics, thermal effects, geochemical reactions, and stress changes. Consequently, numerical methods become essential for the simulation of geothermal reservoirs [19,28,29]. Deep reservoirs are typically characterized by fractures and heterogeneity, necessitating the inclusion of these features in the model. In fractured reservoirs, flow, transport, and geo-mechanical properties are significantly influenced by the fractures. This introduces non-linearity, leading to variations in pressure, temperature, stress, and, consequently, nonlinear behavior in fluid and rock properties.

Moreover, uncertainties arise due to limited measurements and associated costs, resulting in reliance on sparse data for material properties. Therefore, a geological 3D model must encompass heterogeneity, non-linearity, and uncertainty, making detailed geological analysis and modeling crucial for addressing geothermal challenges [5,10,16,22].

The static model should incorporate reservoir characterization procedures, petrophysical parameters, and maps detailing initial heat and stress. On the other hand, the dynamic model should encompass well tests, time-dependent pressure and temperature variations, the impact of stress on permeability and porosity, and historical flow rates for history matching to project heat production forecasts. Beyond these considerations, the models play a pivotal role in determining how to optimize the net present value (NPV) and minimize uncertainties for the techno-economic development of projects.

Multiple Models for Geothermal Reservoir Screening

Before embarking on the development of a geothermal reservoir, it is imperative to conduct a thorough site study based on available data, referred to as project screening. Subsequently, development sites should be systematically ranked, taking into account the associated uncertainties. For geothermal projects, the consideration of land availability becomes paramount, including the location of the plant and its accessibility in relation to urban development and existing infrastructures. Consequently, a preliminary assessment of aquifers is deemed necessary for future development.

In the context of the Lithuanian geothermal system, an analytical and geological screening assessment, complemented by a techno-economic model, has been executed, and the outcomes are detailed in [27]. These findings underscore the substantial potential within depleted oil and gas reservoirs for geothermal development in Lithuania.

5. Application of New Technology

Geothermal production can be operated as a closed-loop system, presenting several advantages, such as emission reductions and efficient water production when meticulous re-injection planning is implemented. Currently, directional drilling and enhanced geothermal systems (EGSs) are two rapidly advancing technologies in geothermal areas, particularly in low-temperature geothermal reservoirs [30].

Detailed 3D modeling surpasses 1D/2D modeling, providing a more accurate representation of geothermal reservoir performance through numerical methods. This is crucial for understanding the interaction between newly injected fluids and existing reservoir fluids, shedding light on the mutual influences between the reservoir rocks and the injected fluids. Cold-water re-injection stimulates the reservoir's mechanical, thermal, and chemical equilibrium, altering porosity and permeability. Hence, the thermal–hydraulic–mechanical–chemical (THMC) model is a key parameter for matching the historical production of the aquifer. It will help to clarify the poro–perm relationships before and after the injection of produced water, influence of precipitation/dissolution kinetics, reservoir mineralogy, and working conditions [4,6,9,12,15,18,22]. A similar modeling approach has been used in the geothermal screening of Lithuanian geothermal complexes in [27], where details of a modeling approach involving THMC-type model construction and use for screening is presented.

THMC modeling together with reactive transport modeling will also help to answer questions about mineral precipitation and a decline in injectivity; some of these issues related to a decline in injectivity have been previously discussed in the context of Lithuanian geothermal development in [5]. The issue of mineral precipitation leads to a reduction in injectivity. In the context of vertical wells, the optimal method for enhancing injectivity is hydraulic fracturing. The induced fracture serves to generate artificial high-permeability zones, thereby boosting injectivity. Additionally, drilling long horizontal injection wells at the reservoir's base presents a promising option for increasing the surface area of injectivity. While this approach has not yet gained commercial traction in the geothermal industry, it holds potential for enhancing injectivity and power output.

For safe and sustainable geothermal resource exploitation, understanding these processes within the reservoir is vital for enhancing efficiency based on chemical and physical conditions and predicting spatial–temporal reservoir behavior. Therefore, field and/or sector-scale modeling becomes crucial for the optimization process.

Moreover, in recent times, artificial intelligence (AI) and machine learning (ML) methods have been employed to tackle complex scientific and engineering problems, including surface crack detection, solving partial differential equations, upscaling, and time series forecasting. In this research, the aim is to use machine learning and artificial intelligence to develop a multiphysics model for describing geothermal reservoirs [19,20]. Machine learning, being an iterative process utilizing data to unveil underlying patterns, is well suited for solving inverse problems related to geothermal reservoir modeling.

AI and ML technologies can also help in developing data-oriented history matching models, like the AI- and ML-based history matching approach proposed in [31]; additionally, AI and ML methods can also be used to quantify porosity and permeability trends, which can be used for THMC modeling, as proposed in [32]. Numerical simulations in geothermal reservoir modeling provide valuable insights into the behavior and characteristics of subsurface formations. Leveraging these simulations as inputs for neural network models presents a promising approach to enhancing predictive capabilities and optimizing geothermal energy production. For instance, the authors in [33] demonstrated the effectiveness of this approach by utilizing simulated heat production data as input for a backpropagation neural network model. Their study revealed a strong agreement between the simulated data and the predictions generated by the neural network model. This integration of numerical simulations and neural network modeling opens up new avenues for predicting heat production in geothermal fields without the need for extensive simulation efforts.

Machine learning (ML) algorithms offer further opportunities for reservoir characterization and production performance prediction. ML algorithms can analyze reservoir properties such as porosity, permeability, depth, and temperature to provide comprehensive reservoir characterization [34]. Various ML algorithms, including k-means clustering, artificial neural networks (ANNs), and backpropagation neural networks (BPNNs), have been successfully employed in geothermal reservoir engineering. For instance, k-means clustering facilitates the identification of distinct reservoir zones with unique characteristics [35], while ANNs and BPNNs excel at learning complex relationships between input variables and production outcomes. These algorithms have been Instrumental in enhancing geothermal well drilling strategies [36] and predicting reservoir production with improved accuracy [37].

Furthermore, the pressure and temperature changes in geothermal reservoirs may result in significantly impacting permeability and porosity. Understanding these changes helps to unravel the geological complexity of the geothermal reservoir [38–40]. It is important to adopt a data-driven approach to quantify changes induced in reservoir properties over time due to fluid injection and production. AI and ML models should also be developed using either measured data or by using data from published literature or pseudo-models generated through numerical modeling approaches for a Lithuanian geothermal reservoir. Furthermore, AI and ML models could also be employed to generate time series forecasts of energy production.

6. Ways Forward

The geothermal potential in Lithuania has been evaluated analytically by numerous researchers [2–6,9–13,15,16,19–22]. Until 2004, only one geothermal computer model had been developed [8]. Consequently, recognizing the necessity for a comprehensive 3D model to explore the geothermal potential, we initiated this research. Furthermore, the Klaipeda Geothermal Plant (KGDP) grapples with issues related to mineral precipitation, biological activity, and gasification. Therefore, developing a THMC model becomes imperative for defining mineral solubility, particles originating from field operations, and gypsum precipitation.

In the realm of geothermal reservoir simulations, aside from studying well spacing for thermal breakthrough, we will delve into re-injection strategies. This encompasses evaluating injection at the top or bottom of the production well, as well as re-injection temperature. The variation in rates is a critical consideration that must be determined to alleviate side effects in re-injection sites close to production wells or those with good connectivity. Establishing rate limits in specific wells and monitoring water chemistry can enhance rate management. Moreover, the development of a THMC model aids in a detailed understanding of salt and mineral deposition and the effects of non-condensable gases within the system.

Also, this paper discusses only technical aspects of underground modeling to assess the viability of geothermal energy production in Lithuania. This is performed so that the further investigation could have some sort of grounding to move forward. Having said that, we acknowledge the importance of economics in such matters and have already started working on preliminary techno-economical calculations.

During the course of the review presented in this paper, some of the most important reports regarding the operation of the Klaipeda Geothermal Demonstration Plant (KGDP), which was the only geothermal plant in Lithuania, were looked into. Excluding the problems with injection and failing to implement effective countermeasures for remediation of the wellbores, there were a considerable number of comments in these reports regarding the energy sector condition, some of which have been documented in some published papers. For example, references [1,2] mention the research, policy measures for development, decentralization of heating industry, with ownership transferred to municipalities, and privatization as a way to create a favorable framework for geothermal energy. Reference [6] underscores that the economic viability of geothermal energy in Lithuania is sensitive to the quantity of heat extracted and the price at which it is sold. The major challenges that geothermal heat industry face here are obtaining access to the market and a profitable fixed minimum price for heat. Reference [4] hints at external funding from EU programs as being highly beneficial (or even necessary). Reference [41] has one of the biggest claims regarding economics, saying that there is a heat monopoly that rules the central heat network, which is operated by the heat suppliers. They dictate the prices to independent heat producers. A favorable legal basis is very important in order to make geothermal energy production viable in Lithuania. For example, extracting geothermal energy requires additional electricity and chemicals, but this is offset by the savings in emission allowances.

Moving forward into a more techno-economic standpoint, several industries—oil producers in Lithuania with experience in deeper wellbore drilling—were contacted in order to acquire estimates for drilling, wellbore rework, site maintenance costs, etc. In order to obtain the precise numbers, each industry must be contacted individually. Former KGDP personnel supplied additional information on what must be implemented as well in order to have a fully functioning power plant, like heat pumps, exchangers, boilers, pipelines, contracts with municipalities, etc. These have significantly changed since the KGDP beginnings, not only in costs but in the efficiency of each aggregate as well.

Also, a rather new geothermal power plant is starting operation in Denmark with the help of the company Innargi A/S, which is one of the models that we should look up to. They were also contacted on a techno-economic evaluation of the project that they are implementing. The main idea to be extracted in such early stages of development is that it comes down to heat production cost—EUR/MWh. Subsurface models, which are starting to be developed in the reference paper [27] for geothermal screening, give us the energy output, whereas the city gives the demand depending on its size.

Techniques to be used are vast and will be addressed with time. One of them to be implemented on a high level could be the concept of a duration curve—it plots the demand in MW for each hour across the year. It tells how many hours of a year the produced heat can be sold and gives the MWh for the EUR/MWh calculation. For a very simple analysis, a sample duration curve with the same shape for all cities of interest could be used by scaling the peak demand to the district heating network size or population size. It is also feasible to acquire the competitor house heating costs in Lithuania.

Another crucial factor to address is the distance to the city as the heat transfer pipeline cost is high and the efficiency in terms of energy loss in the pipeline is considerable. Transporting geothermal water over long distances is not advisable, even due to factors such as chemical processes, like the risk of scaling.

There are numerous factors to consider and techno-economic analysis cannot fit under a simple algorithm. Thus, we are hesitant to call all of this a “methodology” per se, as all of this can vary significantly on the country laws, economic situation for each industry, awareness, etc. Such work is only carried out during the gradual implementation and through feasibility studies such as this paper.

As for the environmental aspect, some of the common misconceptions on deep geothermal energy production is the potential damage toward the overall environmental health. Since the wells are very deep, in excess of 2 km or more, the water there is highly saline and not fit for consumption for local ecosystems. Also, this water is separated from potable water via a very extensive large and thick shale barrier, which prevents any possibility of communication/contamination between these two systems. This water is also naturally kept deep underground by caprock inside aquifers. Water produced for drinking in Lithuania is at maximum 500 m deep, but usually at only 200 m depth, which is more shallow than the depth that deep geothermal wells reach.

One of the potential dangers with any subsurface resource production is the tectonic activities triggering a seismics response; however, Lithuania has practiced oil and gas extraction for many years and has not had any seismic incidence in the past, and the area is not dominated by tectonic plate movements. There is also no mention of abnormal seismic activity in any of the available KGDP reports.

7. Summary

The compilation of studies on Lithuanian geothermal exploration and utilization provides a comprehensive overview. Key findings include insights into geothermal fields such as the Vydmantai Geothermal Field and the identification of potential in hot dry rocks (HDRs) and sedimentary aquifers. Operational challenges, exemplified by injectivity issues in the KGDP plant, underscore the need for international cooperation. The studies delve into the geo-environmental impact, hydrochemistry, and soft stimulation concepts. Moreover, the evaluation of well designs, re-injection strategies, and optimization methods contributes to understanding geothermal development challenges.

The application of AI tools, numerical simulations, and innovative techniques such as radial jet technology aims to enhance geothermal utilization by addressing uncertainties and ensuring sustainability. This literature review delineates the past and present studies while highlighting the gaps in determining the potential of the geothermal situation in Lithuania. This article also details the establishment of new technologies and involvement of industry partnership to solve complex geothermal problems using 3D models for Lithuanian geothermal complexes.

Leveraging geothermal reservoir simulation, a sensitivity analysis will be conducted to actively determine the most effective parameters. Additionally, the re-injection practice must be redeveloped to minimize uncertainty. Recording production tests, water temperature, and water rates is imperative for updating the dynamic model for history matching and generating production forecasts. The necessity of THMC models is emphasized to capture mineral dissolution and/or precipitation, biological activity, and corrosion.

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