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Integrated energy-efficiency assessment of a geothermal well doublet digital twin for oil and gas fields

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Abstract

Purpose. The research aims to develop and validate an integrated approach to assessing the digital twin of a geothermal well doublet system, which, within a single computational scheme, combines inter-well filtration, heat transfer within the wellbore, pump flow rates and the realistic low-temperature cogeneration potential. In addition, the purpose of research is to form a model suitable for operational decision-making and preliminary technical-economic assessments in conditions where electricity cogeneration is treated as a derivative component of heat extraction, limited by allowable drawdown and the heat-transfer fluid circulation mode in oil-and-gas-type collectors.

Methods. An integrated modelling methodology was employed, comprising a radially generalized filtration model based on Darcy's law, a modified Shukhov's model for assessing heat losses in the wellbore column taking into account a velocity correction, as well as an energy module for determining pump power and a model for assessing the electrical power of low-temperature cogeneration. A parametric analysis was performed for a series of calculation scenarios, based on which an empirical multiplicative dependence of useful thermal power was identified and a dimensionless integral efficiency criterion was formed for constructing stable operating ranges.

Findings. It has been found that the useful thermal power of a geothermal doublet varies between 0.2-0.99 MW, while the potential for electricity cogeneration is 15-75 kW, or about 4-7% of the thermal power. It is shown that maximizing debit is not equivalent to maximizing useful energy due to the rapid growth in pump flow rates and heat losses in the wells. It has been determined that the optimal operating modes of the doublet should be based on an integral energy criterion, and not only on hydrodynamic parameters.

Originality. An integrated thermohydraulic-energy core for a geothermal doublet digital twin has been developed and validated, in which filtration, heat transfer, heat losses, pump flow rates and cogeneration are combined into a single analytically consistent model. For the first time, a multiplicative empirical formula for assessing useful thermal power has been synthesized, and an energy-consistent criterion for selecting operating modes of a geothermal doublet system has been proposed.

Practical implications. The proposed approach forms an engineering-appropriate basis for the rapid selection of debits, well depths, and nominal drainage radii, which make it possible to determine stable operating modes of geothermal doublets, reduce energy losses, limit pumping loads, and reasonably assess the thermal potential of oil and gas conversion projects.

Keywords: *geothermal doublet; low-potential geothermal energy; digital twin; cogeneration; heat losses in the well; Darcy's law of filtration*

1. Introduction

Low-potential geothermal systems are increasingly viewed as a key component of decentralized heat supply, fourth- and fifth-generation low-temperature heating networks, and hybrid energy infrastructures in which thermal energy can be combined with heat pumps and auxiliary cogeneration of electricity. Such systems are particularly promising for regions with developed well infrastructure and a high demand for sustainable local heat supply, particularly in areas with old oil-gas and mining development [1]-[3]. Unlike high-temperature geothermal fields, spatially limited by zones of active volcanism and abnormally high heat flows, low-temperature geothermal resources are much more widespread and can be attracted through aquifers of shallow and medium depths, primarily using the geothermal well-doublet scheme [4]-[6]. This approach is particularly important in the context of reusing the existing oil-gas well stock, where depleted or low-debit hydrocarbon wells are considered not only as decommissioned assets of the mining industry, but as a potential base for geothermal heat production [7], [8]. This transformation makes it possible to combine the energy utilization of existing underground infrastructure, a reduction in capital expenditure on drilling, and the expansion of the practical use of geothermal energy within the concept of sustainable development of mineral, raw material, fuel and energy resources [9]-[11].

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Current research into geothermal well-doublet systems focuses primarily on detailed thermohydromechanical (THM) modelling of filtration and heat transfer processes within the reservoir [12]-[14], assessing the impact of geological structure and tectonic change on reservoir productivity [15], as well as optimizing well placement and operating modes, taking into account parameter uncertainty [16]-[18]. These approaches actively develop numerical platforms and open simulation environments (in particular, ComPASS), enabling the implementation of complex multi-physics problem formulations under realistic geological conditions [19].

A particular area of modern research is concerned with the formation of digital geothermal system twins, which combine geological models, monitoring data and adaptive numerical algorithms to support real-time operational decisions [20], [21]. Such approaches increasingly integrate data from distributed sensor systems, including fibre-optic methods and DAS monitoring, enabling the monitoring of the thermo-hydraulic and seismic reservoir behavior [22], [23].

At the same time, most existing studies focus either on the reservoir level (assessment of debit, heat extraction, drawdown, induced seismic activity) or on the energy level (heat networks, accumulation, consumption optimization), without forming a single integrated framework for assessing the efficiency of a geothermal doublet as a holistic energy system [24], [25].

Traditional approaches to calculating the productivity of geothermal wells are based on Darcy's filtration models and semi-analytical debit estimates for given permeability values, effective thickness and allowable drawdown [26]. Heat losses in wells are traditionally analyzed within stationary or quasi-stationary heat transfer models along the wellbore [27]. The low-temperature conversion of the extracted heat is considered separately – either through Organic Rankine Cycles (ORC) [28], or through Stirling-type external combustion engines [29], typically without direct connection with the hydrodynamic and thermal restrictions of the reservoir.

As a result of such a fragmentary approach, a significant methodological gap remains in the scientific literature: there is no integral parametric model within which well depth, production horizon properties, heat-transfer fluid circulation rate, heat losses in wells, pump flow rates for inter-well filtration, and the potential for low-temperature cogeneration are analyzed together.

Moreover, in most studies, electrical cogeneration is treated as an independent goal, whereas in low-potential geothermal systems it is of a derivative nature and is fundamentally dependent on the cooling mode of the circulating heat-transfer fluid, allowable drawdowns, and thermal breakthrough between wells [16], [17]. This limits the possibility of a correct engineering and operational assessment of the actual energy feasibility of integrating the thermal and electrical use of a geothermal resource, which in turn affects the decisions to choose pairs of well-doublets and the need to invest in refining the achievable technical and economic indicators.

In this regard, the transition from local models to an integral digital twin of a geothermal doublet is relevant (Fig. 1), focused not only on filtration and thermal processes within the reservoir and external processes around the geothermal reservoir, but also on a systematic assessment of useful thermal power, pump flow rates, and the achievable potential of low-temperature cogeneration, taking into account the actual permissible operational restrictions.

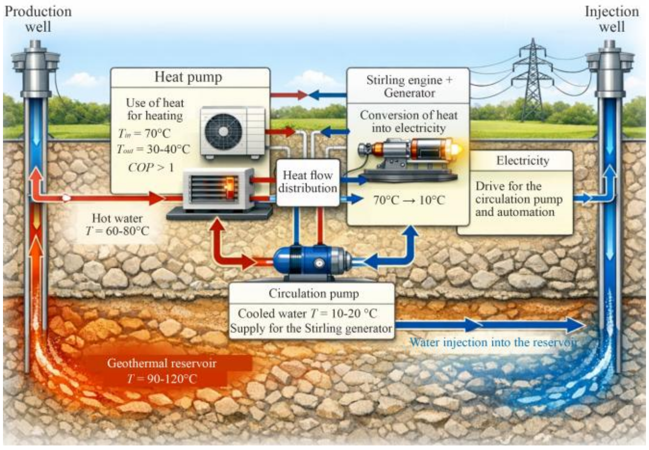

Figure 1. Technological and hydrogeological scheme of the geothermal doublet digital twin

The purpose of this research is to develop and validate an integrated approach to assessing the efficiency of a digital twin of a geothermal well-doublet system operating in a mode of parallel heat extraction and low-temperature cogeneration of electricity. To achieve the set purpose, the following objectives were solved during the research:

1. Formalize a coherent thermohydraulic model of a geothermal doublet that incorporates reservoir filtration, heat inflow from the surrounding rock mass, heat transfer within the wells, and circulation losses.

2. Perform a parametric analysis of the influence of well depth, permeability, nominal drainage radius, and effective thickness of the production horizon on the debit, useful thermal power, and pump flow rates.

3. Assess the realistic potential of low-temperature cogeneration as a derivative function of the heat-transfer fluid cooling mode and the allowable reservoir drawdown under conditions of hydrodynamic interaction between the production and injection wells.

4. Formulate a generalized empirical dependence for the operational assessment of the useful thermal power of a geothermal doublet within a digital twin, and demonstrate an example of its validation for the Yefremivskyi field in the Dnieper-Donets Depression based on data and approaches given in the applied studies [26], [30], [31].

2. Methods

2.1. Concept of a geothermal doublet as an integrated thermohydraulic system

A geothermal well-doublet system is a closed hydrodynamic system consisting of a production well and an injection well, hydraulically connected through a productive aquifer. The efficiency of such a system is determined not by individual subsystems, but by their interaction: inter-reservoir filtration, heat transfer within the reservoir, heat exchange in wells, and the energy consumption for circulation [12], [13].

Modern approaches to modeling geothermal doublets are based on thermohydromechanically coupled (THM) models, which take into account changes in pressure, temperature, and the stress-strain state of rocks [13], [14]. However, most of these models focus on local issues (stability, induced seismicity, well placement optimization) [32], [33] and rarely generate an integral energy efficiency indicator directly suitable for engineering and technical-economic assessments.

At the same time, an important methodological basis for the development of geothermal well-doublet systems is formed by research focused on digital monitoring of oil-gas facilities, processing and interpretation of geophysical data, optimization of well and surface production systems, as well as improvement in well construction and operation technologies in difficult mining-geological conditions [34]-[39].

Within the framework of the digital twin of a geothermal well-doublet system [20], [21], [25], [40], it is advisable to use a hierarchical model, where:

– the geological block determines the filtration and thermal properties of the reservoir;

– the hydrodynamic block describes inter-well circulation;

– the thermal block takes into account heat losess and heat extraction;

– the energy block assesses pump flow rates and cogeneration potential.

This is precisely the model structure used in this paper.

2.2. A model of inter-well heat-transfer fluid filtration

Inter-well circulation in a homogeneous aquifer is described by the radial form of Darcy's law, which serves as the standard basis for analyzing geothermal doublets [17], [18]:

$$Q = \frac{2\pi kh}{\mu} \cdot \frac{\Delta P}{\ln\left(\frac{R_d}{r_w}\right)}, \tag{1}$$

where:

Q – volumetric flow rate of the heat-transfer fluid;

k – reservoir permeability;

h – effective thickness of the permeable horizon;

μ – dynamic viscosity of the fluid;

ΔP – working drawdown between wells;

R_d – drainage radius;

r_w – well radius.

Unlike classical optimization approaches [16], [17], in this paper, the drawdown is not maximized but is limited to physically permissible values that minimize the risk of thermal inter-well breakthrough and excessive pump flow rates [12].

2.3. Formalization of heat extraction and heat losses in the well

The useful thermal power of a geothermal doublet with convective heat transfer is expressed as:

$$P_{th} = mc_p\left(T_{prod} - T_{inj}\right), \tag{2}$$

where:

$m = Q\,\rho$ – mass flow rate of the heat-transfer fluid.

The temperature at the production wellhead is calculated taking into account the geothermal gradient, convective heat transfer, and heat losses in the wellbore, which is consistent with modern models of heat transfer in wells [18], [27].

The conductive heat inflow to the drainage zone at depths greater than 1 km is assumed to be quasi-spherical from the surrounding rock mass, while heat extraction occurs through the lateral surface, roof and bottom of the cylindrical drainage zone of injection and production wells. After substituting values based on the geometric and physical logic of the process, we obtain a complete integral model that accounts for the full volumetric heat inflow:

$$P_{conv} = 4\pi\lambda_r\left(h + R_d\right)\left(1 + \frac{h}{2R_d}\right)\left(T_0 + GL - \frac{\left(T_{prod} - T_{inj}\right)}{2}\right). \tag{3}$$

Formula (3) implements an integral model for assessing the convective heat inflow from the surrounding rocks to the permeable part of the cylindrical drainage zone of a geothermal doublet, which accounts for the spherical nature of heat transfer from a conditionally infinite medium and heat transfer through the lateral surface, roof and bottom of the reservoir, which limits the geothermal production capacity even in cases of sufficient and intensive convective heat transfer within the permeable reservoir itself (2). Thus, the thermal efficiency (1)-(2) is speed-dependent through m and T_{prod}, which is often ignored in simplified approaches [24].

2.4. Energy consumption for circulation

The pump power is determined as:

$$P_{pump} = \frac{Q \cdot \Delta P}{\eta_{pump}}, \tag{4}$$

where:

η_{pump} – efficiency of the pump unit.

In this research, pump flow rates are directly incorporated into the integral efficiency balance, which is consistent with the recommendations for modern digital twins of energy systems [20], [25].

2.5. Low-temperature cogeneration model

The electrical power of cogeneration is assessed based on the thermodynamic efficiency of low-temperature heat engines:

$$P_{el} = \eta_{el} \cdot P_{th}, \tag{5}$$

where:

η_{el} – for realistic conditions is 0.04-0.07 for ORC and Stirling engines [29], [41].

It is of fundamental importance that, in this research electricity is considered as a derivative cooling effect of the heat-transfer fluid, rather than as a self-sufficient goal of exploiting low-potential geothermal resources. The key parameters of the model and its unit of measurement, as presented in the results section, are shown in Table 1.

2.6. Integral efficiency indicator for a digital twin

The generalized indicator of the geothermal doublet efficiency Φ is proposed in the form:

$$\Phi = \frac{P_{th} - P_{el} - P_{pump}}{P_{pump}}. \tag{6}$$

This dimensionless criterion makes it possible to compare different geometries and depths, define stable operating ranges, and integrate the model directly into the digital twin [20], [21], [40]. Analyze the filtration model in the reservoir between the doublet wells. For circulation to work between the injection and production wells, the condition must be met that the sum of the drainage radii is greater than or at least equal to the distance between the bottomholes L_d. Therefore, in the digital twin model, conditionally assume $L_d = 2r_e$ (this minimizes the circulation pump power and the risk of thermal breakthrough under conditions of the allowable maximum reservoir drawdown $\Delta P = (P_e\text{-}P_w)_{\max}$. Consequently, methodologically and in the following calculation and analytical options, the substitution of the minimum allowable bottomhole pressure of the injection well is used, which prevents the washout of rock that would disrupt the filtration and heat exchange zones of both wells.

Table 1. List and numerical ranges of the input and output parameters of the geothermal doublet digital twin

Designations	Parameter name	Unit of measurement (SI)	Typical range	Comment / role in the model
k	Reservoir permeability	m^2	$5\cdot10^{-14}$-$1.5\cdot10^{-13}$	Filtration conductivity; linearly affects the debit
h	Effective horizon thickness	m	20, 30, 40, 50	Linear contribution to debit and thermal power
L	Well depth	m	1500-3000	Compromise: gradient/heat loss/pump flow rates
$R_d= ½ L_d$	Drainage radius	m	200, 400, 600, 800	Logarithmic filtration resistance; effect on debit and safe drawdown
r_w	Effective well radius	m	0.1	In the logarithmic Darcy/Dupuit term
D	Internal diameter of pump-compressor pipes	m	0.062	Determines flow velocity and hydraulic losses
ρ	Geothermal water density	kg/m³	980	In the debit, thermal power, and pump calculations
μ	Dynamic viscosity	Pa·s	$6\cdot10^{-4}$	In Darcy's formula and hydraulic losses
c_p	Specific heat capacity of water	J/(kg·K)	4200	To calculate thermal power
p_e	Reservoir pressure	Pa	$27\cdot10^6$	Upper limit for allowable drawdown
p_w	Bottomhole pressure (allowable)	Pa	$26.5\cdot10^6$	Forms the maximum safe drawdown
ΔP	Allowable drawdown on the reservoir	Pa	$5\cdot10^5$	Limit for safe operation
Λ	Hydraulic friction coefficient (Darcy-Weisbach)	–	0.03	Hydraulic losses in the column
α_0, α_{eff}	Effective heat loss coefficient	1/m	0.05	Shukhov's model with a velocity correction
G	Geothermal gradient	°C/100m	0.03	Determines the temperature at the bottomhole
T_b	Bottomhole temperature	°C	90	Initial condition for heat losses
T_0	Ambient temperature (wellhead)	°C	10	Maximum ambient temperature
T_{prod}	Temperature at the production wellhead	°C	54-100	Depends on Q and L (Shukhov's model)
T_{inj}	Injection temperature	°C	10	After heat exchange
Q	Debit (m^3/s)	m^3/s	0.0006-0.0028	Determined using Darcy's law; affects losses and power
v	Velocity in pump-compressor pipes	m/s	0.19-0.94	Affects heat losses and hydraulic losses
ΔP_{tr}	Loss of pressure on rise (friction)	Pa	$1.1\cdot10^5$-$3.3\cdot10^6$	Proportional to v^2 and L / D
ΔP_{total}	Total pressure loss	Pa	$1.5\cdot10^7$-$2.9\cdot10^7$	Total of rise + injection + reservoir
P_{pump}	Pump capacity	W	$1.15\cdot10^3$-$3.1\cdot10^4$	$Q\cdot\Delta P / \eta$
P_{th}	Useful thermal power	W	$2.0\cdot10^5$-$1.0\cdot10^6$	Main energy product
P_{el}	Electrical power (cogeneration)	W	$1.4\cdot10^4$-$7.0\cdot10^4$	≈ 4-7% of P_{th}
Φ	Integral efficiency indicator	–	–	Heat/pump/electricity balance
P_{geo}	Integral thermal power according to the formulas (2) or (11)	W	$2.5\cdot10^5$-$1.1\cdot10^6$	Function of k, h, L, R_d
P_{conv}	Thermal power of conductive-spherical inflow	W	$2.5\cdot10^5$-$1.1\cdot10^6$	Function of λ_r, h, L, R_d

Unlike the traditional setting of a radial inflow to a single well (1), in the case of a geothermal doublet, the filtration field is formed by the interaction between the injection and production wells. In the quasi-stationary approximation for $L_d = 2r_e$, the volumetric circulation debit can be the theoretically determined pressure drop between them and the logarithmic hydraulic resistance between the bottomholes:

$$Q = \frac{2\pi kh}{\mu} \cdot \frac{2\Delta P}{\ln\left(\left(4r_e^2 - r_w^2\right)/r_w^2\right)}. \quad (7)$$

Thus, we retain quasi-stationary filtration, but we provide an effective logarithmic resistance between the two wells corresponding to a realistic and refined nominal drainage radius in geological-technological practice.

Consider hydraulic losses and pump power. The total pressure losses for closed-loop circulation through the circuit of the injection and production wells are calculated as twice the hydraulic flow rates of the geothermal fluid being pumped up and down, plus the hydraulic losses due to reservoir drawdown:

$$\Delta p_{total} = 2\lambda \frac{L}{D} \cdot \frac{\rho v^2}{2} + 2\Delta P. \quad (8)$$

Form an extended Shukhov's formula. The classical Shukhov's formula describes the exponential cooling of the fluid in a pipeline due to heat exchange with the environment. For a geothermal well, it must be widened, as the fluid flows at a finite velocity. Its heat-transfer fluid residence time in the column is determined by the debit, and the ambient temperature changes with depth according to the geothermal gradient.

The energy balance along an elementary section of the well leads to the following analytical solution:

$$T_{wellhead} = T_0 + \left(T_b - T_0 - GL\right)\exp\left(-\frac{\alpha_{eff} L}{\rho c_p Q}\right). \quad (9)$$

Apply the correction to Shukhov's coefficient, taking into account the velocity. The effective heat loss coefficient α_{eff} is introduced as a function of the fluid velocity:

$$\alpha_{eff} = \alpha_0 \cdot \frac{v_0}{v}, \quad (10)$$

where:

v – average velocity in the column;

α_0 – the basic value of the Shukhov's coefficient, determined for the reference velocity v_0. Thus, lower velocities (longer rise times) automatically lead to more intense heat losses during the rise of the heat-transfer fluid to the surface.

3. Results

3.1. Calculation results based on the developed model

The input data and calculation results for the model based on the system of Equations (1)-(10) are given in Table 2, supplementing the Table 1 with specific substitutitions of values for the calculation options. The input data are based on the averaged characteristics of geothermal doublets previously modelled for the re-equipment of previously inactive oil and gas fund of wells in the Yefremivskyi gas condensate field of the Dnieper-Donets Depression [30]. This served as validating model adequacy test based on evidence from [26], [30], [31]. To construct parametric diagrams and curves, the depth range, permeability of the production reservoir and its thickness (acting height of the exposed thickness) were changed to 16 calculation options based on Dependences (1)-(9) relative to a basic set of initial parameters (Table 1).

Analysis of 16 parametric options (Table 2) showed that the reservoir permeability k linearly scales the debit in accordance with Darcy's law and, consequently, the useful thermal power P_{th}. Within the range ($k = 5 \cdot 10^{-14}$-$2 \cdot 10^{-13}$ m^2), the dependence of $P_{th}(k)$ is practically linear. A similar nature of influence was determined for the effective thickness of the production horizon h, the contribution of which to the formation of P_{th} is also close to linear. At the same time, the well depth L influences the thermal power in two ways: positively – through an increase in temperature at the T_b bottomhole due to the geothermal gradient, and negatively – through increased heat losses and pump flow rates during the rise of the heat-transfer fluid. As a result, the dependence $P_{th}(L)$ is sublinear in nature and is well described by a power-law approximation with the index 0.4-0.6.

In all cases, when the debit and the corresponding hydraulic circulation flow rates increase, the coefficient Φ decreases (Table 2), as it represents the ratio of net extractable geothermal power to the power required to drive the circulation pump P_{pump}. However, this also increases the potential for electricity generation through P_{el} cogeneration, which forms a generally optimizing technical-economic task.

Table 2. Results of modelling a geothermal doublet digital twin with basic input parameters and varying 4 of them (16 parametric options)

Option	Parameter (group)	Figure	Q, m³/s	T_{prod}, °C	P_{th}, W	P_{el}, W	Φ	P_{conv}, W	P_{pump}, W
1	h	20	0.0011	84.8	401655.9	28115.9	118.9	793374.8	3584.1
2		30	0.0017	84.7	601573.6	42110.2	74.3	817528.5	8543.3
3		40	0.0023	84.5	800884.3	56061.9	48.5	842037.2	17303.2
4		50	0.0028	84.4	999588.2	69971.2	33.3	866901.8	31130.7
5	L	1500	0.0011	54.8	240508.1	16835.6	87.5	543429.9	2908.4
6		2000	0.0011	69.8	321082.0	22475.7	104.8	668402.3	3246.3
7		2500	0.0011	84.8	401655.9	28115.9	118.9	793374.8	3584.1
8		3000	0.0011	99.8	482229.9	33756.1	130.6	918347.2	3921.9
9	k	5e-14	0.0006	84.9	201131.4	14079.2	184.7	792433.5	1158.6
10		1e-13	0.0011	84.8	401655.9	28115.9	118.9	793374.8	3584.1
11		1.5e-13	0.0017	84.7	601573.6	42110.2	74.3	794316.1	8543.3
12		2e-13	0.0023	84.5	800884.3	56061.9	48.5	795257.3	17303.2
13	R_d	200	0.0006	84.9	223314.3	15632.0	177.1	345166.2	1341.3
14		400	0.0012	84.8	411597.8	28811.8	116.1	643981.8	3760.1
15		600	0.0017	84.7	589948.4	41296.4	76.3	943909.0	8162.6
16		800	0.0022	84.6	762223.8	53355.7	52.5	1244552.5	15244.9

3.2. The influence of hydrogeological parameters on debit and circulation flow rates

Parametric calculations of a geothermal doublet digital twin show that the key factors determining the achievable circulation debit are the permeability of the production horizon, its effective thickness, and the allowable drawdown between the production and injection wells. The results obtained confirm the known analytical dependences based on Darcy's law, but reveal significant non-linearities when moving to realistic inter-well spacings and restrictions on maximum pressure drops [17], [26].

For typical permeability values ($k = 10^{-14}$-10^{-12} m^2) and effective thickness of the horizon (h = 20-80 m), the increase in debit occurs quasi-linearly only within a limited range of allowable drawdowns. Further increase in pressure drop leads to a sharp rise in pump flow rates and a decrease in the overall energy efficiency of the system, which is consistent with the conclusions of optimization studies of geothermal doublets under conditions of parametric uncertainty [16]-[18]. Furthermore, convective heat transfer in the middle of the drainage zone according to (2), at a certain excess of drawdown on the reservoir, begins to prevail the possible conductive-spherical heat pump effect in accordance with the design of Formula (3). That is, an increase in circulation rate will not provide a guaranteed long-term corresponding increase in geothermal power (Fig. 2).

Figure 2 shows that the anti-destructive restriction on reservoir drawdown initially imposes a restriction on production capacity along the curve of convective intra-reservoir heat transfer (increases linearly with increasing debits simultaneously with drawdown). However, after passing the point of 0.7 MPa, the conductive restriction already makes it impossible to grow (will be determined after passing this point) along the almost horizontal curve of spherical-conductive energy extraction from rocks to the production reservoir.

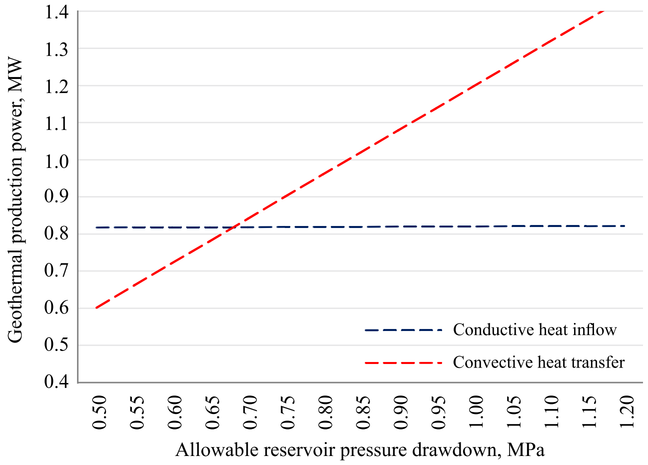

Figure 2. Dependence of conductive-spherical and convective geothermal production in units of power on the reservoir drawdown

Thus, the results of modelling using the parameters of digital twins of validation doublets from [26], [30], [31] confirm that maximizing debit is not equivalent to maximizing useful energy, and that permissible operating modes should be determined based on integral energy criteria, and not only hydrodynamic indicators.

3.3. Heat extraction and the role of heat losses in wells

Heat balance calculations show that for low-potential geothermal systems, heat losses in the wellbore play a significant role and cannot be neglected, even at relatively high circulation debits. As well depths increase from 1.5 to 4.0 km, the share of heat losses in the wells increases disproportionately; this is due to the increase in the length of the heat exchange surface and the temperature gradient between the fluid and the surrounding rocks [27].

The results obtained are consistent with classical models of heat transfer in wells [41], but at the same time demonstrate that when heat losses are integrated into a digital twin, the optimal range of circulation velocities changes significantly. An excessive increase in debit leads to an increase in pump flow rates without equivalent increase in useful thermal power on the surface.

As a result, the thermal power of a geothermal doublet should be considered as a function not only of the geothermal gradient and depth, but also of the coordinated circulation mode, which confirms the need for the integrated approach proposed in the studies [12], [24], [42].

3.4. Assessment of the potential for low-temperature cogeneration

Based on the obtained temperature regimes and available useful thermal power, the potential for low-temperature cogeneration of electricity using external heat engines was assessed. The analysis showed that, for typical heat-transfer fluid temperatures at the wellhead (T = 60-110°C), a realistic heat-to-electricity conversion coefficient does not exceed 4-7%, regardless of the type of converter (ORC or Stirling engine) [29].

The results of the assessed electricity generation percentages (Table 2) are fundamentally consistent with current reviews of low-temperature technologies [28], [29], but within the context of a digital twin, they acquire significant systemic importance: electric cogeneration is a derived parameter that is strictly limited by the cooling mode of the heat-transfer fluid, the allowable reservoir drawdown and the requirements for long-term reservoir stability [1], [16].

Thus, within the framework of the proposed approach, electricity is treated not as an independent optimization goal, but as a secondary, parameter-dependent efficiency indicator, which avoids inflated expectations regarding the energy efficiency of low-potential geothermal systems.

3.5. Integral efficiency indicator

Based on a series of numerical experiments, a generalized empirical dependence is formed for assessing the useful thermal power of a geothermal doublet as a function of well depth, permeability and the effective thickness of the production horizon. The proposed integral efficiency indicator Φ analytically combines the useful thermal power on the surface, pump flow rates for inter-well circulation, allowable operational restrictions for drawdown, and the potential for low-temperature cogeneration.

This approach is consistent with current concepts of digital twins for geothermal systems, focused on supporting engineering solutions and preliminary technical-economic assessments [20], [21], [25], [40].

The results obtained show that, within the parameter ranges considered, the thermal power of the geothermal doublet P_{th} varies from 0.2 to 0.99 MW (Table 2), while the achievable electrical power remains at the level of the auxiliary component. This confirms the feasibility of a systematic approach to the design of geothermal doublets, in which priority is given to sustainable thermal use of the resource, while cogeneration is considered as an additional energy bonus, rather than as a determining criterion for efficiency.

3.6. Structure of the developed empirical formula for the integral assessment of the thermal power of the geothermal doublet digital twin

Based on Table 2, according to Formulas (2)-(10) and the physics of the process, the expediency of engineering use of a multiplicative empirical form of the integral thermal power assessment of a geothermal doublet digital twin of the following form has been revealed:

$$P_{geo} = C\left(\frac{k}{k_0}\right)\left(\frac{h}{h_0}\right)\left(\frac{L}{L_0}\right)^{\beta} \cdot \left(\frac{\ln\left(R_d / r_w\right)}{\ln\left(R_{d_0} / r_w\right)}\right)^{\gamma}. \quad (11)$$

The standard values for permeability k_0, effective thickness of the production reservoir h_0, the exposure depth of the production horizon L_0 and the basic useful power of geothermal production P_b are taken as the parameters of the basic option given in Table 1, as well as taking into account the validation digital twin parameters of the Yefremivskyi gas condensate field wells [30].

In particular, the following was adopted: $k_0 = 10^{-13}$ m^2; h_0 = 30 m; L_0 = 2500 m; C ≈ 6.5·10^5 W. Within such a parametric field, the application of a power-law depth exponent in the integral assessment model of useful power P_{geo}, determined based on the results of validation options for several digital twins [30], [31] in the range L = 1500-3000 m, yielded a generalized value $\beta \approx 0.5$. The resulting value accurately reflects both the decline in production efficiency at shallow depths and the gradual saturation of the useful power with increasing well depth.

Based on parametric calculations of the digital twin, a generalized thermohydraulic model and the identification of coefficients using the results of 16 scenarios, a final engineering multiplicative Formula (11), has been derived, which enables the useful thermal power of a geothermal doublet to be assessed as a function of four key parameters: the permeability of the exposed production horizon, the effective thickness of the permeable reservoir, the well depth at the bottomhole, and the nominal drainage radius comparable to the distance between wells (the safe drawdown margin for the reservoir).

These parameters determine both the filtration conductivity of the reservoir, as well as the thermal and energy balance of the heat-transfer fluid circulation. Consistency with the modeling results is ensured by introducing normalization coefficients and a power-law exponent β, which reproduces the compromise between the geothermal gradient, heat losses in the wellbore and pump flow rate at different depths.

We obtain the final integral validation formula for the Yefremivskyi gas condensate field for engineering and applied assessments of the following form:

$$P_{geo} = 6.5 \cdot 10^5 \left(\frac{k}{10^{-13}}\right)\left(\frac{h}{30}\right)\left(\frac{L}{2500}\right)^{0.5} \cdot \left(\frac{\ln\left(R_d / r_w\right)}{\ln\left(500/0.1\right)}\right)^{\gamma}, \quad (12)$$

where:

$\gamma \approx 1$ – sensitivity indicator to the geometric factor of drainage between wells.

The conducted parametric study of pilot implementation of a digital twin using a typical scheme (Fig. 1) shows that the model adopted for the theoretical geothermal doublet validation of the Yefremivskyi gas condensate field adequately reproduces the main patterns of its energy efficiency formation. In particular, the effective thickness of the aquifer has been found to have an almost linear effect on the thermal power of geothermal extraction. As the well depth increases, the contribution of the geothermal gradient to the fluid temperature rises; however, the pumping power required to lift the heat-transfer fluid also increases significantly. Reservoir permeability is a determining factor in the system efficiency, particularly in the conditions of implementing electrical cogeneration, as it is this factor that determines the permissible debits at acceptable hydraulic losses.

For the analyzed configurations and geological-industrial observations of the old oil and gas fund of the well, the thermal power of the Yefremivskyi gas condensate field doublet varies approximately between 0.2 and 0.99 MW, as well as while the potential for electrical cogeneration is 15-75 kW (Table 2), corresponding to 4-7% of the extracted thermal energy (consistent with data from sources [27]-[29], [41]).

Assuming the drainage radius to be equal to half the inter-well spacing proved to be a permissible and physically sound approximation for the preliminary assessment of the operational safety modes of a geothermal doublet, provided there is no reservoir anisotropy and radial filtration dominates.

4. Discussion

The key scientific contribution of this research is the integration of known hydrodynamic and thermal dependences into a single analytically consistent model suitable for the engineering analysis of geothermal doublets. The operational diagrams constructed enabled the identification of mode ranges within which cogeneration of electricity is thermodynamically feasible and does not lead to a deterioration in the main heat supply.

The principle result is the identification of a practical upper power limit, determined not by the equipment nominal rating, but by the available exergy of the heat flow and the allowable operational drawdown. In this context, electricity is regarded as a by-product of heat extraction, suitable for covering own needs or driving pumps, but not as an independent goal of operating a low-potential resource. This approach corrects the widespread optimistic interpretations of ORC potential in low-temperature systems and is of applied importance for doublet planning.

The proposed Darcy's law form for a doublet system determines the hydrodynamic upper limit of inter-well circulation, while the complete thermohydraulic digital twin scheme forms an energetically consistent range of safe debits, automatically taking into account head losses, velocity effects and pumping feasibility. This enables a shift from point optimization of parameters to the formation of stable operating ranges adapted to specific geological-hydrodynamic conditions.

A comparison with recent thermohydromechanical studies confirms a general pattern: an increase in debit is accompanied by a disproportionate increase in pump flow rates and a balance between heat extraction and long-term reservoir stability [16]-[18], [42]. The distinctive feature of the proposed approach consists in introducing a single integral energy criterion that directly combines useful thermal power, electrical cogeneration and the energy consumption of the pumps. This makes the model suitable for rapid feasibility studies and early design decisions, unlike studies that focus primarily on reservoir behaviour.

Compared to digital twin approaches focused on monitoring and predicting asset condition, the proposed framework implements an engineering-simplified digital twin that maintains physical transparency and avoids the excessive complexity of full-scale CFD/THM models. Its key feature is multi-block integration (reservoir filtration, heat loss in the wellbore, pump flow rates, cogeneration) and the formation of a generalized criterion for constructing operational diagrams [20], [21], [25], [40].

Taking into account the velocity correction to the heat transfer coefficient allows the residence time of the heat-transfer fluid in the column to be accurately reflected, which is critical for low-potential systems. It is shown that an excessive increase in debit leads to a decrease in the maximum energy efficiency due to a rapid increase in P_{pump}, not compensated by a corresponding increase in P_{th}, which is generally consistent with classical concepts regarding the energy limitations of geothermal systems [27].

The electrical cogeneration range obtained in this research, at 4-7% of the useful heat flow, generally corresponds to the estimates given in studies on low-temperature ORC and Stirling systems [28], [29], [41]. However, within the proposed approach, electrical energy is interpreted as an auxiliary component of the thermal cycle, and not as an independent goal of operating a low-potential geothermal resource.

In this research, an integral thermohydraulic-energy model for digital twin has been developed and validated for the first time for geothermal doubles formed on the basis of re-equipped oil and gas fields; this model systematically combines three traditionally separate subsystems of the research object, namely: filtration-thermal processes in the reservoir (the object in the classical sense), heat transfer in the wellbore, energy consumption and the thermodynamic potential of low-temperature cogeneration. Thus, a single integral core capable of describing the complete circulation loop of the heat-transfer fluid was formed, expanding the classical scope of research into geothermal doublets by parametrically covering at least four key (most influential) efficiency factors: the permeability of the production horizon k, the effective thickness of the reservoir h, the well depth L and the nominal drainage radius R_d. It is these parameters that are combined into a coherent multiplicative theoretical model (1)-(10) and an empirical useful power model (11-12), reproducing the real energy compromises of the system and can serve as a preliminary technological design. In particular, the proposed approach expands the methodological toolkit for assessing the energy efficiency of a geothermal doublet, as it incorporates a velocity correction to Shukhov's heat loss coefficient $\alpha_{eф}$, which reflects the actual residence time of the heat-transfer fluid in the column, formalizes the volumetric conductive-spherical heat inflow as a factor in the marginal heat productivity of the reservoir and provides analytical coordination of pump flow rates, filtration resistance and heat losses within a single energy cycle.

An engineering-appropriate, empirically validated Formula (12) has been developed for the rapid determination of the useful thermal power of geothermal doublets in the Yefremivskyi field; this formula has physically interpreted coefficients, is consistent with full THM-calculations, provides stable accuracy within 5-20% across the investigated parameter ranges, and enables rapid technical-economic comparison of scenarios even before the start of full-scale CFD-modelling. Multivariate modeling and calculations with validation ranges for the input parameters (Table 1) substantiate an energy-constrained conclusion that electrical cogeneration is a secondary parameter of heat extraction, and not an independent goal. It is shown that its value is determined by the allowable drawdown, heat losses and the cooling mode of the heat-transfer fluid, and not merely by the temperature potentials of the ORC/Stirling engines.

The practical significance of this research is the creation of an operationally suitable tool for the design and management of geothermal doublets, which provides engineers with clear guidelines for selecting optimal modes of debit and depth, based not on maximizing flow rate, but on an energy-based balance between heat transfer and pump flow rates, and allows stable operating ranges to be formed directly within the digital twin for real wells, the risk of thermal breakthrough between production and injection wells to be assessed, and the limits of allowable reservoir drawdown to be determined. The developed mathematical apparatus provides a directly applicable basis for the preliminary feasibility study (FS) of geothermal projects, including the selection of well pairs for conversion and the calculation of expected thermal and electrical productivity.

The general novelty and value of this research lies in: creating a single integral core for hydrodynamic, thermal and operational processes; introducing an energy-consistent criterion for the formation of operating ranges; the proposed empirical engineering-level formula with physically interpreted parameters; the interpretation of electricity generation as a by-product of heat extraction, which complements the Blitz-THM and reduced-order numerical models, transforming their results into direct engineering decision-making rules.

5. Conclusions

A generalized integral model for a geothermal doublet digital twin has been developed, which, within a single physically consistent computational scheme, combines radial inter-well filtration, heat transfer in the wellbore column, taking into account the heat-transfer fluid velocity, pump flow rates and the potential for low-temperature cogeneration. A parametric analysis of 16 calculation options confirmed the dominant influence of permeability and effective thickness of the production horizon on debit and useful thermal power, and also revealed a non-linear compromise in the influence of well depth, at which an increase in temperature potential due to the geothermal gradient is accompanied by an increase in heat losses and pump flow rates. The importance of taking into account the volumetric conductive-spherical heat inflow from the surrounding rock mass into the permeable reservoir as a factor limiting the long-term thermal productivity of the system is also shown.

An empirical formula is proposed for the rapid assessment of the useful thermal power of a geothermal doublet as a function of permeability, effective reservoir thickness, well depth and nominal drainage radius. Within the validation range studied, it accurately reproduces the results of full numerical modelling for thermal power of 0.2-0.99 MW, providing a compact and practical suitable alternative to complex THM-models at the preliminary engineering assessment stage. The integral efficiency criterion introduced makes it possible to identify stable operating ranges in which an increase in debit does not contradict the energy feasibility of operation.

It has been found that electrical cogeneration in low-potential geothermal systems is a derivative component of heat extraction, limited by the allowable reservoir drawdown, heat losses in the wells and the heat-transfer fluid circulation mode. For the studied conditions, its potential is 4-7% of the useful thermal power without any significant deterioration in the thermal mode of the system. This confirms the expediency of considering cogeneration as an auxiliary energy effect rather than as an independent goal of geothermal doublet operation.

The digital twin model developed has demonstrated its ability to integrally account for the interaction of hydrodynamic, thermal and operational parameters and can be used to support engineering decisions during the conversion of oil and gas wells into geothermal wells. The proposed analytical and parametric apparatus forms the basis for further scaling to real fields, optimizing operating modes and integration with modern low-temperature energy technologies. The combination of an integral efficiency indicator and an empirical formula provides a rational balance between accuracy, ease of use and prompt decision-making, thus making the proposed methodology a promising tool for the design and adaptive management of low-potential geothermal systems.

Author contributions

Conceptualization: MF, IF1; Data curation: MF, IF1, IF2; Formal analysis: MF, IF1, IF2; Funding acquisition: MF, IF1; Investigation: MF, IF1, OF; Methodology: MF, OF; Project administration: MF, OF; Resources: MF, OF; Software: MF, OF, IF2; Supervision: MF, OF; Validation: MF, IF1, IF2; Visualization: MF, IF2; Writing – original draft: MF, IF1, OF, IF2; Writing – review & editing: MF, IF1, OF, IF2. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Інтегральна оцінка енергоефективності цифрового двійника геотермального дублету свердловин нафтогазових родовищ

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Мета. Розробити та валідувати інтегральний підхід до оцінювання цифрового двійника геотермального дублету свердловин, який у межах єдиної розрахункової схеми поєднує міжсвердловинну фільтрацію, теплоперенесення у стовбурі свердловини, насосні витрати та реалістичний потенціал низькотемпературної когенерації. Сформувати модель, придатну для прийняття операційних рішень і попередніх техніко-економічних оцінок в умовах, коли електрична когенерація розглядається як похідна складова тепловідбору, обмежена допустимою депресією та режимом циркуляції теплоносія в колекторах нафтогазового типу.

Методика. Використано інтегральну методологію моделювання, що включає радіально узагальнену фільтраційну модель на основі закону Дарсі, модифіковану модель Шухова для оцінки тепловтрат у колоні свердловини з урахуванням швидкісної поправки, енергетичний модуль для визначення насосної потужності та модель оцінювання електричної потужності низькотемпературної когенерації. Параметричний аналіз виконано для серії розрахункових сценаріїв, на основі яких ідентифіковано емпіричну мультиплікативну залежність корисної теплової потужності та сформовано безрозмірний інтегральний критерій ефективності для побудови стійких операційних областей.

Результати. Встановлено, що корисна теплова потужність геотермального дублету змінюється в межах 0.2-0.99 МВт, тоді як потенціал електричної когенерації становить 15-75 кВт, або близько 4-7% від теплової потужності. Показано, що максимізація дебіту не є еквівалентною максимізації корисної енергії через випереджальне зростання насосних витрат і тепловтрат у свердловинах. Визначено, що оптимальні режими роботи дублету мають встановлюватися на основі інтегрального енергетичного критерію, а не лише за гідродинамічними показниками.

Наукова новизна. Розроблено та валідовано інтегральне термогідравлічно-енергетичне ядро цифрового двійника геотермального дублету, у якому фільтрація, теплоперенесення, тепловтрати, насосні витрати та когенерація об'єднані в єдину аналітично узгоджену модель. Вперше синтезовано мультиплікативну емпіричну формулу для оцінювання корисної теплової потужності та запропоновано енергетично узгоджений критерій вибору операційних режимів геотермального дублету.

Практична значимість. Запропонований підхід формує інженерно придатну основу для оперативного вибору дебітів, глибин свердловин і умовних радіусів дренування, що дозволяє визначати стійкі режими роботи геотермальних дублетів, зменшувати енергетичні втрати, обмежувати насосне навантаження та обґрунтовано оцінювати теплову перспективність проєктів конверсії нафтових і газових свердловин.

Ключові слова: *геотермальний дублет; низькопотенційна геотермальна енергія; цифровий двійник; когенерація; тепловтрати у свердловині; фільтрація Дарсі*

Publisher's note