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Energy Production from Carbon Storage Reservoir

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Abstract

Depleted petroleum reservoirs are considered as the best underground facilities for carbon dioxide storage. The underground storage reservoirs are subject to the constant geothermal heat flux coming from the surrounded formations. Thus, there is an opportunity for further development of these projects for energy production if a sufficient temperature difference is reached between hot CO_2 and cold ambient conditions. This is a great potential to satisfy raising national energy demand. The proposed design contains a single well energy conversion system that could eliminate building a traditional power plant at the surface facility and pumping geo-fluid to the surface. The method can be applied to the existing petroleum wells commissioned for an abandonment. Theoretically, up to 250 kW net power can be achieved from a single well at 125℃ reservoir temperature. This power unit has high efficiency of 15% and low Levelized Cost of Electricity (LCOE). Computed LCOE is in a good agreement with the references and shows competitive results with fossil fuel power plants. Additionally, the unit is compact and requires minimum surface facility footprint comparing with geothermal technologies. The combination of several wells into a power production unit opens an opportunity to generate up to 1 MW and more. All of the mentioned advantages lead to a quick payback of the investment. As a result, the new application can significantly reduce economic load associated with the CO_2 pumping and storage.

Introduction

The geological sequestration of CO_2 in the depleted oil and gas reservoirs was mentioned in a literature as a smooth transition from the carbon dioxide flooding used for “releasing” the residual oil from the formation (Shaw& Bachu, 2002. Mamora & Seo, 2002, Li et al., 2006). Ideally, carbon dioxide can be pumped in a geological trap where it will remain for a long time. This bright idea, however, has many problems required to solve in order to succeed the project. One of them is an economic sustainability of the project. Capturing carbon dioxide in industry, pressurizing, transporting, and injecting into the reservoir is not economically advantageous. The expenses can be reduced if clusters of power plants feed CO_2 into shared transport pipelines. The injection into depleted hydrocarbon fields uses established petroleum industry methods and can commence immediately. Although the total storage capacity in aquifers remains highly uncertain (Haszeldine, 2009, Bridger & Allen, 2005).

Initially, the process of CO_2 storage was presumed to have CO_2 on site. Then pumping it to the underground facility, and afterwards sealing the well. It is worth to mention that carbon dioxide in the reservoir eventually becomes a geo-fluid, which will gain thermal energy from the underground rock formation where the reservoir temperature is a function of depth. A storage facility can be treated as a geothermal storage/power production project if the temperature difference between underground formation and ambient conditions is sufficient enough to install the organic Rankine cycle (ORC) (Brown, 2000). Additionally, power production in traditional way requires building a power plant to utilize produced geo-fluid and later inject it back to the same or another reservoir. This way takes long term installation process and complicated surface facility, however, can be avoided by the new method called Zero Mass Withdrawal (ZMW) power plant.

The new ZMW method of geothermal energy production was proposed recently (Akhmadullin and Tyagi, 2014; Akhmadullin & Tyagi, 2017). This method utilizes Zero Mass Withdrawal principle where the surface facility contains only a condenser part. The rest of the binary cycle is placed inside of a single well. The overall design includes commercially available parts such as pumps, wells, pipes, valves, and can be installed in one trip into the well. Thus, the power unit is easy to assemble during a short period of time right after the CO_2 pumping process is complete. This paper contains proposed design description, thermodynamic and economic analyses with application of various reservoir temperature cases.

Design

The proposed ZMW method requires stored CO_2 circulation inside the reservoir. The well contains production and injection sides where carbon dioxide enters and leaves the well. The downhole pumping equipment creates circulation loop inside the reservoir. Figure 1 shows a case with a horizontal well, however, a vertical well can be considered as well if the thickness of the reservoir is sufficient. In case of using a petroleum production well from the depleted reservoir, a new perforation set is needed to complete the design.

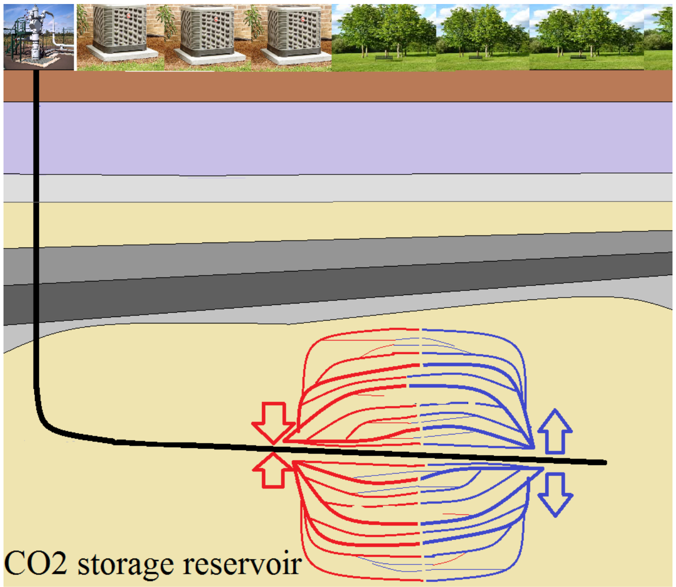

Figure 1 Creating carbon dioxide circulation in the storage reservoir for energy production

The injection and production sides are separated by a sufficient distance to avoid cooled carbon dioxide entering the DHE. Sand control methods can be included in unconsolidated formation applications (Kohshour, 2010; Akhmadullin & Tyagi, 2017). While flowing inside the well, the carbon dioxide passes through the Downhole Heat Exchanger (DHE). The DHE is carrying one more function securing the integrity of the storage reservoir. The stored carbon dioxide serves as a heat transport fluid and does not mix with the binary cycle fluid. A circulation loop inside the reservoir porous media is created by a conventional electric submersible pump (ESP) located in the horizontal offset of the well. The pressure distribution in the horizontal well and main design scheme are shown in the Figure 2. The ESP should have enough pumping head to overcome flow resistances inside the well completion and a reservoir.

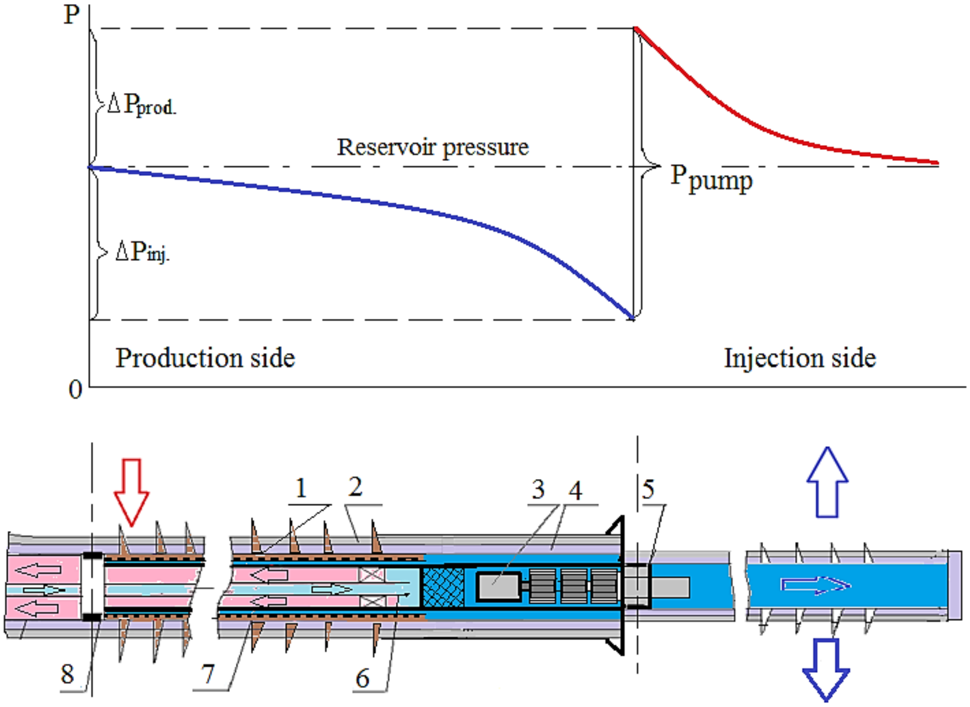

Figure 2 CO_2 pumping system. 1 – Sand screen; 2 – Cement sheath; 3 - Geo-fluid pump; 4 – casing; 5 – Pump packer; 6 – DHE inner tubing; 7 – Perforations; 8 – DHE packer

The vertical part of the well is an essential element of the power conversion unit. There are two working fluid streams. The cold stream is running down from a condenser to the DHE. The working fluid pump is placed at the lowest location of the well such that high hydrostatic pressure is reducing pumping work. The hot stream is rising from the DHE to the surface. The binary cycle parts are installed inside the well (Fig.3). A small turbine is placed inside the well close to the surface on the top of the retrievable packer to provide minimum pressure drop between the turbine and a condenser. The surface facility contains a condenser part and a control unit.

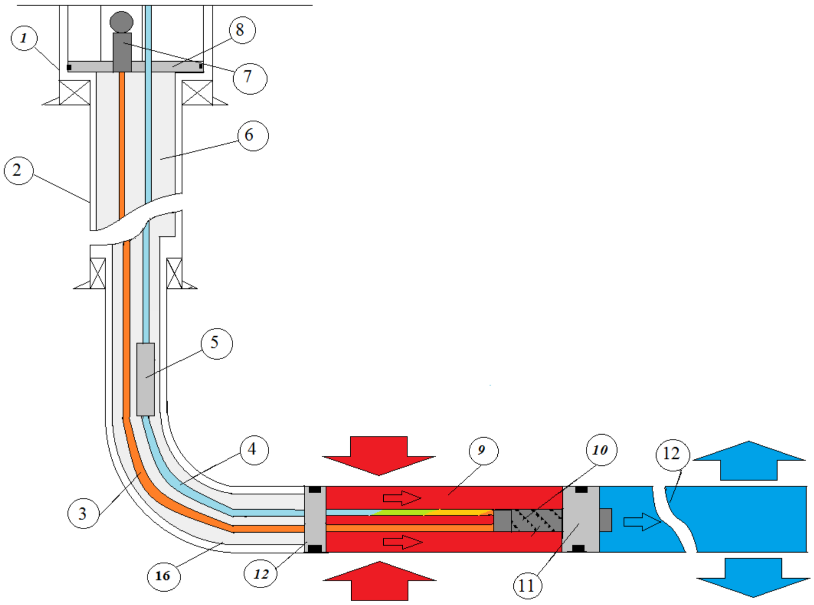

Figure 3 Single well design scheme. 1- surface casing; 2 – intermediate casing; 3 – hot stream; 4 – cold stream; 5 – working fluid pump; 6 – completion fluid; 7 – turbine-generator assembly; 8 – packer; 9 – hot brine from the reservoir; 10 – brine pump; 11-packer; 12 – injection side

Methodology

The nodal analysis was accomplished to determine the thermodynamic properties of the carbon dioxide flowing through the DHE and reservoir and working fluid circulating inside the vertical well (Akhmadullin, 2016). The simulator was performed in Matlab Simulink software. The physical properties of brine and working fluid were tracked for the temperature and pressure conditions at each location of the well. Reservoir flow was tracked using Matlab reservoir simulation toolbox software (K.-A. Lie, 2016).

Input parameters

The input parameters are porosity, permeability, reservoir depth, thickness, reservoir temperature and pressure, well geometry, etc. are shown in the Table 1. As a result of simulation the optimal working fluid and CO_2 flow rates, reservoir discharge temperature and net power production were calculated. More detailed information can be found in Akhmadullin, 2016.

Table 1 Input parameters

Parameter		**Numerical value**
Reservoir	porosity	5-500mD
	permeability	20%
	rock	sandstone
	pressure	80MPa
	temperature	125℃
	thickness	300ft
Well	diameter at the reservoir depth	9inch
	DHE OD	7inch
	perforated length (producer)	750ft

Verification and Validation

The research works of Ouyang et al. (1998) and Feng et al. (2015) were used to verify and validate the computational algorithm. Ouyang explored the flow into the pipe from the porous wall. The cumulative pressure drop inside the pipe was determined as a relationship with the pipe length. As it is seen from the Fig.4 and 5 validation results are matching the reference plots.

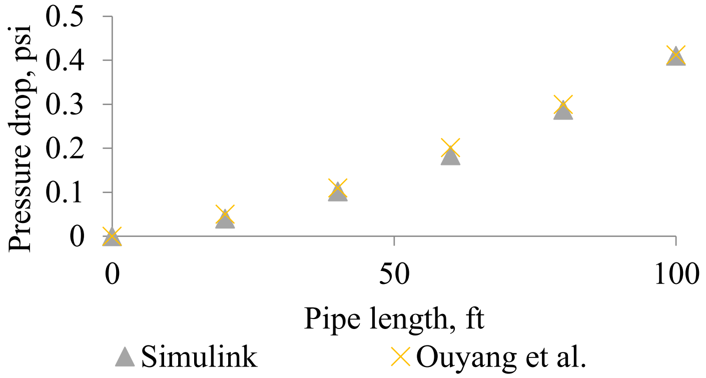

Figure 4 Verification with Ouyang et al. 1998

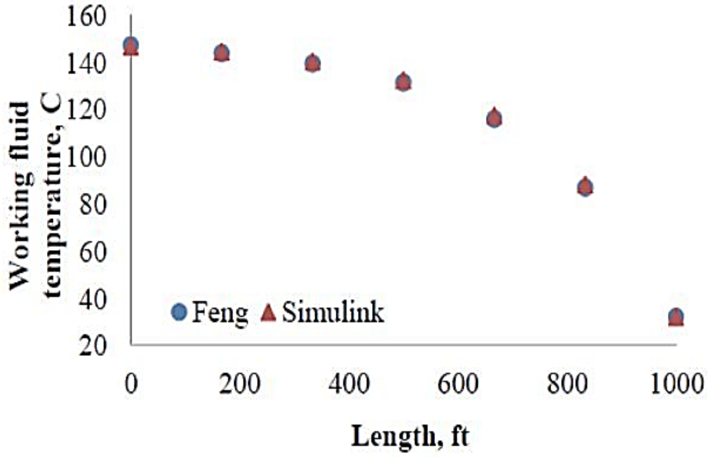

Figure 5 Verification with Feng et al. 2015

Results and Discussions

Working fluid selection

Comparison analysis was performed with several popular fluids (refrigerants R134a, R152a; Hydrocarbons, and CO_2). Carbon dioxide was found as the best working fluid for this design at the range of 100 – 160 ℃ reservoir temperature. Additionally, it is non-toxic, non-flammable, and produces high bottom well pressure, which helps to protect the well from collapsing from the reservoir pressure. CO_2 works well at supercritical cycle and commercially available (Chen et al. 2006). Hydrocarbons only partially convert to vapor at the mentioned temperature range, so require two phase turbine installation, which has less efficiency comparing with single phase expanders. The commercial refrigerants showed the lowest heat transfer properties (Karla, 2012). As it is seen from the Fig. 6 the gross power production from the low enthalpy reservoir is about 300 kW with carbon dioxide as a working fluid.

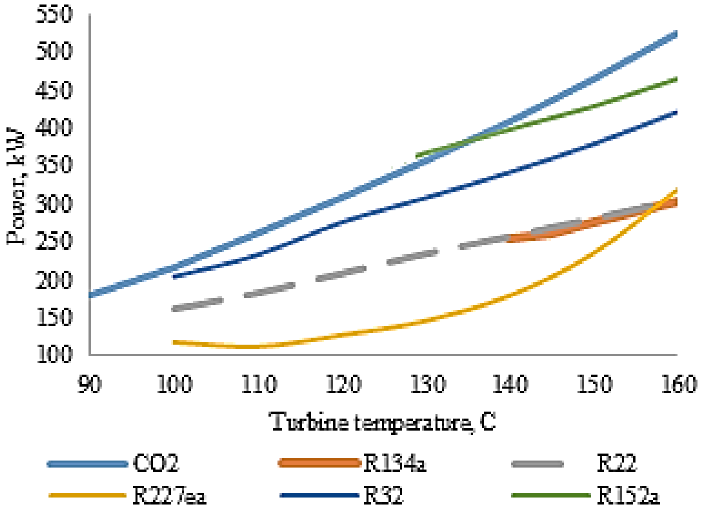

Figure 6 Gross power production by working fluid candidates

The reservoir fluid circulation power is not included into the results. Power consumption depends on reservoir permeability and reservoir fluid flow rate. There is an optimal range of flow rates in terms of net power production (Akhmadullin & Tyagi, 2017). The cold front entering the production side can reduce the power production.

Reservoir response

The simulation solution strategy is well explained by Ansari, 2016. The production and injection sides were placed horizontally inside the 100m thick reservoir. The 10 kg/sec brine flow rate was assumed through the 12 mD permeability and 12% porosity sandstone reservoir with 125℃ temperature. The cold plume of 110℃ was generated during 25 years of non-stop production. As it is seen from the Fig.7 the cold plume is moving down under the gravity force and toward the producer due to the lower pressure intake.

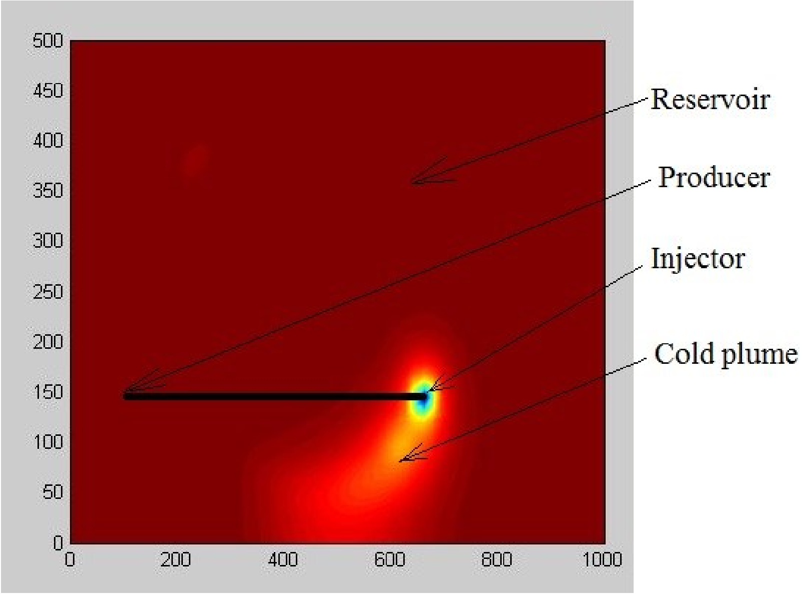

Figure 7 Reservoir simulation results with horizontal well

The following formula was used to analyze the breakthrough time (BTT) (Akhmadullin, 2016, Luo, & Kitanidis, 2004).

$$t_{th} = \frac{4\pi\phi R_t {c_i}^2}{3q}$$

where ϕ is reservoir porosity, c_i is half distance from producer to injector; q is a flow rate; and R_t is retardation factor obtained from:

$$R_t = 1 + \frac{(1-\phi)\rho_{rock.}Cp_{rock.}}{\phi\rho_{br.}Cp_{br.}}$$

The simulation results of the breakthrough time are illustrated in Fig. 8 for a various porosity cases and reservoir CO_2 flow rates. With decreasing the reservoir porosity down to 0.05 the breakthrough time is increasing due to rising the friction forces in the porous media. Reducing the flow rate also enhance the BTT. The optimal flow rate of 6,000 Bbl/day is matching the 25-30 years of production in 0.2 porous reservoir.

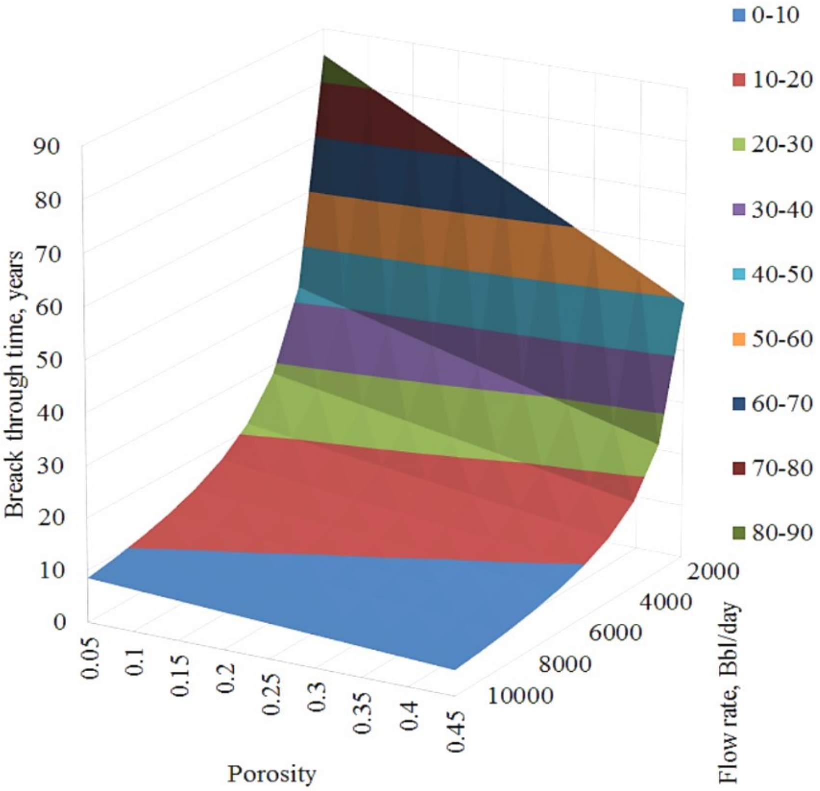

Figure 8 Breakthrough time calculations for 900m insulation interval

Economics

The economic evaluation of the project was performed according to Smith (2005), Walraven (2015), and Randebergi (2012). The Levelized Cost of Electricity was tracked for two cases of reservoir temperature with four wells joined together with the binary cycle. The drilling cost was omitted from the economic model.

Findings:

Ignoring drilling costs, which constitute up to 65% of the project, the LCOE is very attractive for the reservoirs with higher temperature. Figures 9 and 10 show the results.

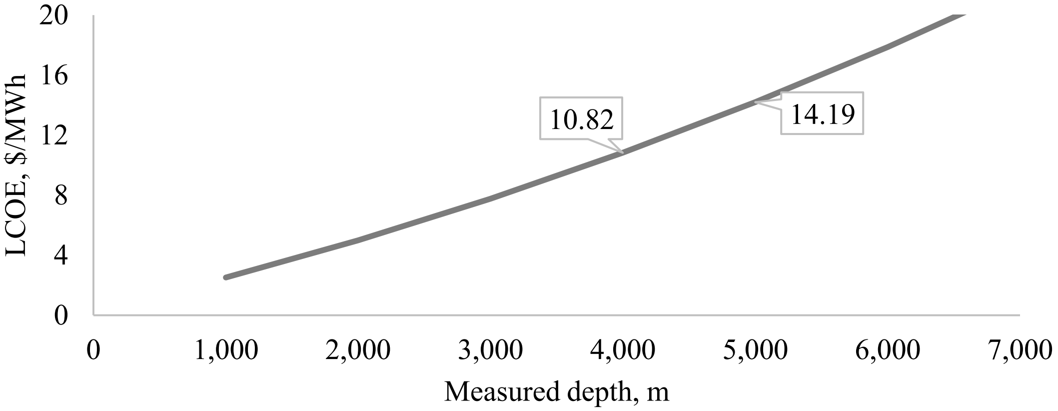

Figure 9 Simulation results for LCOE with 220C reservoir temperature. Four wells working in assembly.

For 4,000m and 5,000m depths the LCOE is shown in the graphs. As it is seen the reservoir having 4,000 m depth and 220C temperature delivers power at 10.82 $/MWh. The deeper location deliver more gross power, but require some expenses for the components of the binary plant. The frictional losses in the system increase and require more power spending to pumps. While considering moderate to low temperature reservoirs the LCOE lies in the range of 46.47 to 60.95 $/MWh.

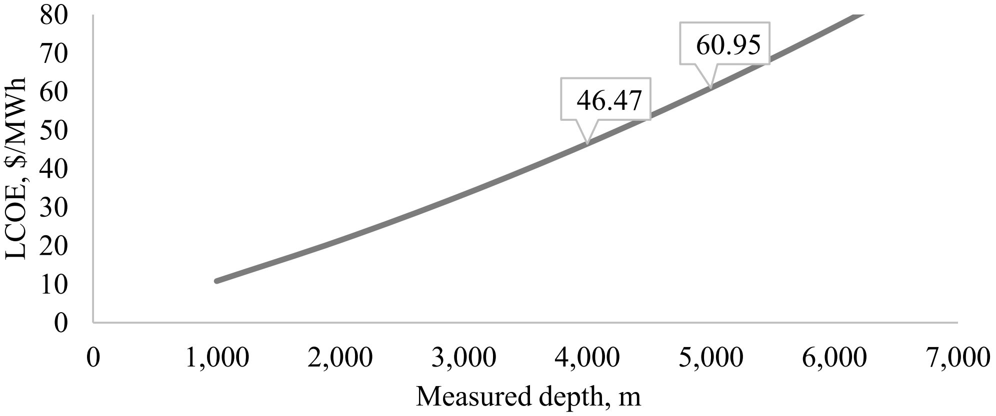

Figure 10 Simulation results for LCOE with 125 C reservoir temperature. Four wells working in assembly.

Conclusions

The new method of power production was introduced. The design of the system is proven its sustainability by economic and thermodynamic analyses. The system is applicable for the petroleum wells used in carbon storage reservoirs.

- The reservoirs with higher temperatures economically more attractive
- The carbon dioxide and R154a named as the best fit binary fluids for this design schemes
- The operational time is constrained by the distance between the producer and injector.

Technical challenges of well recompletion:

In order to complete the project the potential well should have a casing program with 7-9 inch casing on the bottom. The new set of perforations is required to have two: production and injection sides.

In conclusion, this new power production technology is proposed for a modern energy infrastructure and gives zero carbon emission to the atmosphere. It has a short term of assembling facility and competitive price of the produced electric power. This innovative proposal is the next generation of a combination of CO_2 storage and energy production. In general, this design can be assembled from commercially available parts such as pumps, wells, pipes, and valves, etc. Thus, the power unit is easy to assemble during a short period of time.

References

1. Akhmadullin, I., & Tyagi, M. (2014). Design and Analysis of Electric Power Production Unit for Low Enthalpy Geothermal Reservoir Applications. *World Academy of Science, Engineering and Technology, International Journal of Environmental, Chemical, Ecological, Geological and Geophysical Engineering*, *8*(6), 443-449.

2. Akhmadullin I., (2016). Design and Analysis of Geothermal Wellbore Energy Conversion System Working on Zero Mass Withdrawal Principle (Doctoral dissertation, Louisiana State University).

3. Akhmadullin, I., & Tyagi, M. (2017). Numerical analysis of downhole heat exchanger designed for geothermal energy production. *Geothermal Energy*, *5*(1), 13.

4. Ansari, E. (2016). Mathematical Scaling and Statistical Modeling of Geopressured Geothermal Reservoirs (Doctoral dissertation, Louisiana State University).

5. Bridger, D. W., & Allen, D. M. (2005). Designing aquifer thermal energy storage systems. *ASHRAE JOURNAL*, *47*(9), S32.

6. Brown, D. W. (2000). A hot dry rock geothermal energy concept utilizing supercritical CO_2 instead of water. In *Proceedings of the twenty-fifth workshop on geothermal reservoir engineering, Stanford University* (pp. 233-238).

7. Chen, Y., Lundqvist, P., Johansson, A., & Platell, P. (2006). A comparative study of the carbon dioxide transcritical power cycle compared with an organic Rankine cycle with R123 as working fluid in waste heat recovery. *Applied Thermal Engineering*, *26*(17), 2142-2147.

8. Feng, Y., Tyagi, M., & White, C. D. (2015). A downhole heat exchanger for horizontal wells in low-enthalpy geopressured geothermal brine reservoirs. *Geothermics*, *53*, 368-378.

9. Haszeldine, R. S. (2009). Carbon capture and storage: how green can black be? Science, 325 (5948), 1647 – 1652.

10. K.-A. Lie. (2016). An Introduction to Reservoir Simulation Using MATLAB: User guide for the Matlab Reservoir Simulation Toolbox (MRST). SINTEF ICT.

11. Kalra, C., Becquin, G., Jackson, J., Laursen, A. L., Chen, H., Myers, K. ... & Zia, J. (2012). High-Potential Working Fluids and Cycle Concepts for Next-Generation Binary Organic Rankine Cycle for Enhanced Geothermal Systems. In *37th Workshop on Geothermal Reservoir Engineering, Stanford, CA*.

12. Kohshour, I. O., Habibnia, B., & Ghobadi, H. (2010). Sand Control Study and Assessing Suitability of Installing Expandable Sand Screens (ESS) in Comparison with IGP in Cased and Open Hole Wells in Mansou. In *4th EAGE St. Petersburg International Conference and Exhibition on Geosciences-New Discoveries through Integration of Geosciences*.

13. Li, Z., Dong, M., Li, S., & Huang, S. (2006). CO 2 sequestration in depleted oil and gas reservoirs—caprock characterization and storage capacity. *Energy Conversion and Management*, *47*(11), 1372-1382.

14. Luo, J., & Kitanidis, P. K. (2004). Fluid residence times within a recirculation zone created by an extraction–injection well pair. *Journal of Hydrology*, *295*(1), 149-162.

15. Leung, D. Y., Caramanna, G., & Maroto-Valer, M. M. (2014). An overview of current status of carbon dioxide capture and storage technologies. *Renewable and Sustainable Energy Reviews*, *39*, 426-443.

16. Mamora, D. D., & Seo, J. G. (2002). Enhanced gas recovery by carbon dioxide sequestration in depleted gas reservoirs. In *SPE Annual Technical Conference and Exhibition*. Society of Petroleum Engineers.

17. Ouyang, L. B., & Aziz, K. (1998, January). A simplified approach to couple wellbore flow and reservoir inflow for arbitrary well configurations. In *SPE Annual Technical Conference and Exhibition*. Society of Petroleum Engineers.

18. Randebergi, E., Fordi, E., Nygaardi, G., Erikssonii, M., Gressgardi, L. G., Hanseni, K., (2012). "Potentials for Cost Reduction for Geothermal Well Construction in View of Various Drilling Technologies and Automatization Opportunities". In 36th Workshop on Geothermal Reservoir Engineering, Stanford University. SGP-TR-194.

19. Smith, R. (2005). *Chemical process design*. John Wiley & Sons, Inc.

20. Shaw, J., & Bachu, S. (2002). Screening, evaluation, and ranking of oil reservoirs suitable for CO2-flood EOR and carbon dioxide sequestration. *Journal of Canadian Petroleum Technology*, *41*(09).

21. Walraven, D., Laenen, B., & D'haeseleer, W. (2015). Minimizing the levelized cost of electricity production from low-temperature geothermal heat sources with ORCs: Water or air cooled? *Applied Energy*, *142*, 144-153.