Peer Review Report

Review Report on The value of a hole in coal: Assessment of seasonal thermal energy storage and recovery in flooded coal mines

Original Research, Earth Sci. Syst. Soc.

Reviewer: Billy Andrews
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EVALUATION

Q 1   Please summarize the main findings of the study.

The authors utilise open-source modelling software to assess the behaviour of a simplified 3D mined volume to seasonal heat storage and extraction. Through the analysis of several injection/extraction scenarios the efficiency of two base models, one with a 1 m coal seam and another with a 3 m coal seam, was investigated. The geological conditions of the site, especially coal, was found to greatly impact the efficiency of the system that could reach a maximum efficiency of 45-50%. The authors then compare the heat recovered from the system to the equivalent energy and monetary value of the 'mined' coal.

Q 2   Please highlight the limitations and strengths.

The strength of the work primarily comes from the fact that low enthalpy systems using coal mines as an aquifer for heat have rarely been modelled and that field data for these systems is not yet widely available. Additionally, the comparison of system efficiency to equivalent heat energy is novel and combined with a monetary comparison to traditional energy sources will undoubtedly be useful when communicating the technology with stakeholders in the public and private sector.

The major limitations of the study are due to the simplifications and volumes used in the modelling process. Whilst simplifications are clearly necessary to enable the numerical modelling, it is unclear in the current manuscript that the impact of these simplifications on the modelled results have been fully understood. A particular worry is that the modelled volume chosen is very small compared to sites that would be target for these types of schemes and that the modelling requires a static groundwater system.

Q 3   Please comment on the methods, results and data interpretation. If there are any objective errors, or if the conclusions are not supported, you should detail your concerns.

Whilst the methods in themselves are valid and appropriate for the purposes of the study and data presented clearly, my major concerns surround the assumptions taken when setting up the model. As discussed in my full review, the oversimplification of the rock mass and small volume modelled makes it difficult to assess the works applicability to potential mine water reservoirs. Adding a clear section that discusses the limitations, along with a greater discussion of the gaps that the work does not focus on would help here.

Q 4   Check List

Is the English language of sufficient quality?
    Yes.

Is the quality of the figures and tables satisfactory?
    Yes.

Does the reference list cover the relevant literature adequately and in an unbiased manner?
    Yes.

Are the statistical methods valid and correctly applied? (e.g. sample size, choice of test)
   Yes.

If relevant, are the methods sufficiently documented to allow replication studies?
   Yes.

Are the data underlying the study available in either the article, supplement, or deposited in a repository? (Sequence/expression data, protein/molecule characterizations, annotations, and taxonomy data are required to be deposited in public repositories prior to publication)
   Yes.

Does the study adhere to ethical standards including ethics committee approval and consent procedure?
   Not Applicable.

If relevant, have standard biosecurity and institutional safety procedures been adhered to?
   Not Applicable.

Q 5 **Please provide your detailed review report to the editor and authors (including any comments on the Q4 Check List):**

Dear Jesus Perez Silva and Christopher McDermott,

Please find below my review of your manuscript "The value of a hole in coal: Assessment of seasonal thermal energy storage and recovery in flooded coal mines". I enjoyed reading your manuscript which used a novel way of communicating the value of 'charged' low enthalpy systems utilising flooded coal mines and believe that with a number of revisions this contribution could pave the way for important modelling work as well as improve how the academic community can 'sell' the idea to the commercial sector. The latter point is required if we are too upscale the technology and meet the UKs NetZero goals. Please find below my major and minor comments and should you require any clarification please do not hesitate to get in contact,

Kind regards,
Dr. Billy J. Andrews
University of Plymouth

Major comments
MC1: How representative is the modelled rock mass?
a) Size of the modelled rock mass: One of my main limitations of the paper is that the volume of the modelled rock mass is very low compared to the size of mines that are being targeted for these schemes. Due to the behaviour of the system through time for the small volume case, it is unclear whether a larger mined void would take longer to reach the required equilibrium for maximum efficiency.
b) Mine layout & at-abandonment layout: Reference is made to the layout being geometrically consistent to similar workings, which is indeed consistent with the grid pattern seen in many pre-1930 workings. However, the extraction ration chosen is on the high end of those observed in the UK. The authors also state that the geometry of shallow workings is often unknown, which I don't believe applies to target schemes. Due to the high capital, and often political, risk of these schemes' small workings at very shallow levels would not be a target, with abandonment plans heavily used during the scoping and feasibility stage of any development. Therefore, the 'at time of abandonment' geometry of the system is typically relatively well known (ignoring survey errors/post abandonment pillar robbing). Information about geological faults, seam thickness and seam depth across the worked level is also routinely provided on such plans.
c) The modelling approach considers the lithologies surrounding the worked seam to have a single set of properties. This is despite the highly heterogeneous nature of UK coal measures (e.g., see Fielding's 1980s papers from NE England, or some of the more recent correlation work done by the BGS). A major issue is that organic rich shale and/or paleosols are often found surrounding the worked level, which would behave in a

similar way to the thick coal seam in Model B. A porosity of 15% was taken into the 3D modelling, but it was unclear where this value came from. The vast majority of rocks in the UK Coal measures are tight and require fracture flow to enable any aquifer to form (e.g., O Dochartaigh, B.E., MacDonald, A.M., Fitzsimons, V. and Ward, R., 2015. Scotland's aquifers and groundwater bodies). Additionally, pumping records from UKGEOS suggest that fracture flow dominates the mine water system. Therefore, the rationale behind modelling a static system needs to be clearly communication and/or the limitations of this assumption discussed in conjunction with the results. The use of a single set of rock properties is a large simplification, and for future work could be improved through the use of the rich borehole and/or seam log records held by the BGS.

MC1b: Different mine geometries and post-extraction conditions.
A sub-division of MC1 is the consideration that the mine water reservoir may show variable geometries (e.g., due to the presence of geological structure) and/or have been altered due to post-extraction mine conditions (e.g., stall collapse). Whilst this is clearly out of scope of this study, to be able to discuss efficiency of a system I believe a section needs to be added that discusses the limitations and assumptions made during the modelling process. One of the major unknowns is the volume of water and permeability of the system, which will depend on the volume of workings still assessable to flow (e.g., hasn't collapsed etc).

MC2: Introduction section and placing the results within the net-zero literature
Whist it was clear that using an approach like that utilised in this study could provide a powerful tool to 'sell' the idea to investors and stakeholders in the public and private sectors, I found the manuscript a little difficult to follow in places and the importance of the work was not clearly laid out to the reader. Specifically, there where points that seemed to be unrelated to this contribution and paragraphs that contained several points that where only tentatively linked and would have been better suited in as separate paragraphs. This was compounded by the results not being set within the current literature surrounding net-zero and low enthalpy geothermal systems. Each of the results sections add value to the literature, however, placing it within the limited modelling done to date on uncharged systems would help the reader see why, despite the number of limitations of the modelling approach, this work significantly advances the field.

Line by line comments
No (Line) Comment
1 (13-15) Given the number of caveats in the modelling and mine system, the statement that 45% of the energy could be recovered seems a bit overly optimistic. The statement should be linked to caveats in the abstract, which is briefly addressed in the main text, to avoid this becoming the expected value for such schemes. This is particularly the case due to do the very small volume modelled here compared to sites that are currently being targeted.
2 (54-57) Consider rearranging the start of the paragraph to split the global and high latitude problem, as well as improve flow and readability. Maybe to "The space heating sector contributes 51% of global energy consumption (REN21, 2019) and represents a complex challenge to the ongoing energy transition. This is particularly true for high-latitude regions where space heating represents a major source of CO2 emissions as well as having high ramp-up rates and seasonal fluctuation in demand (Figure 1)." The sector…
3 (63) 'A large-scale implementation of this option' – I assume here you are referring to district heating networks? It is currently a little ambiguous.
4 (64) Does Lund and Boyd not discuss higher enthalpy geothermal systems? The sentence would still work without the however point, which is not linked to the low enthalpy heat storage situations you model.
5 (65) Satisfactory groundwater flow is a major uncertainty in these schemes and can be influenced by several post-mining conditions. See MC1b.
6 (68) Whilst these flow rates can be obtained, it is not a certainty. Consider rewording to may allow rates above 100 m3h-1.
7 (69) There are several authors who have listed current and planned geothermal schemes, as well as some UK based schemes that are in the pipeline which have lower capacity that 500kW. Whilst I agree it is an under-utilised resource this point could be made with more reference to the current literature.
8 (71-74) Whilst this is true, I struggle to see the relevance to the research presented in this manuscript.
9 (78) Heerlen is a far greater scale than that modelled in this study. As a reader I would want to see justification for the small 'heat reservoir' chosen related to the schemes that are at the planning and/or operational stage.

10 (84) Remove 'in the field' – Is this scheme currently in the planning phase? If so I would ensure this is stated at the start instead of using pioneering development.

11 (89) The variability of the mine system, or reservoir, is a major limitation to the simplified modelling approach used in this study. This is particularly the case for pillar and stall mines where pillar orientation and spacing varied in the vicinity of geological structures and various mine features (e.g., ventilation shafts, adits etc.). You also don't mention the different mining methods, in particular 'longwall' and 'pillar and stall', and it should be clearly noted that you are modelling the latter within the introduction. This method was relatively widespread in NE England, but less so in Wales and MVS where longwall/short wall methods were taken up at an earlier period of time (or local methods like Ayrshire short wall).

I also don't agree with the statement 'where many workings usually have no official record of existence'. Whilst it is true that very shallow workings that predate c. 1850, or <30ish meters depth, may be unrecorded these would then not be chosen as a target for heat storage. The UK in particular has a very good mine record due to mine abandonment plans, and the record in parts of Europe is also exceptional. This should be highlighted and is in fact used during the feasibility assessment stage of such schemes.

12 (90–99) I agree that the adverse conditions need to be raised, however, one clear omission is the uncertainties in flow-rate/mine conditions following closure. The data from UKGEOS show evidence of partially collapsed voids, high permeability fracture networks overlying voids, and clay rich fills at mined levels. Additionally, this is raised in the accompanying paper by Alison Monaghan that came out this year.

Drilling into mines for heat: geological synthesis of the UK Geoenergy Observatory in Glasgow and implications for mine water heat resources

Monaghan, A.A., Starcher, V., Barron, H.F., Shorter, K., Walker–Verkuil, K., Elsome, J., Kearsey, T., Arkley, S., Hannis, S. and Callaghan, E., 2021. Drilling into mines for heat: geological synthesis of the UK Geoenergy Observatory in Glasgow and implications for mine water heat resources. Quarterly Journal of Engineering Geology and Hydrogeology.

Additionally, for an example at depth I refer to a borehole record in Northumberland in my 2020 Geothermics paper that tackles the issues of stall collapse in pillar and stall mines ->

Collapse processes in abandoned pillar and stall coal mines: implications for shallow mine geothermal energy

Andrews, B.J., Cumberpatch, Z.A., Shipton, Z.K. and Lord, R., 2020. Collapse processes in abandoned pillar and stall coal mines: implications for shallow mine geothermal energy. Geothermics, 88, p.101904.

Could these also effect the assumption of porous flow above the workings? The height of the fracture network above pillar and stall mines can be considerable, with the subsidence literature a good place to start when considering this (e.g., Garrads 1980s papers).

13 (111) You discuss porosity of the host lithologies, however, porosity Is often highly variable within the surrounding lithologies, ranging from tight sands, shales and channel sandstones. How appropriate is it to assign a single, high end, porosity value to the CRS? Particularly due to the presence of fracture dominated aquifers within the coal bearing top–delta successions.

14 (117)

15 (127–128) The modelled void volume of 2340 m3 would represent a very small mine at a scale that is far below what would be targeted for heat storage schemes. Is there a reason for why this value was chosen? Would you expect significant differences if a scheme–scale mine was modelled. Similarly, what effect would varying the geometry (e.g., due to the presence of geological structure) have on the modelled results. Whilst it may be beyond scope of this study, I strongly suggest adding a sub–section that discusses this either in the methods or discussion section.

16 (142–148) A fundamental assumption behind the study is that the system behaves as a static system. However, there is evidence from UKGEOS and historical pumping data from mines that relatively quick responses to meteorological events are evidenced. Additionally, fracture flow often dominates at the mine level as well as in several Carboniferous Aquifers. This assumption could significantly change the modelling results

and there should be a clear rational presented as to why a quasi-stationary porous rock-mass was chosen to run the 3D model.

17 (152) Whilst a mine water temperature of 12 degrees at 150m is reasonable, there is several instances where the mine-water temperature gradient did not match the geothermal gradient. For further information can I suggest looking at Gareth Farr et al.s recent paper on UK mine water temperatures.

The temperature of Britain's coalfields

Farr, G., Busby, J., Wyatt, L., Crooks, J., Schofield, D.I. and Holden, A., 2021. The temperature of Britain's coalfields. Quarterly Journal of Engineering Geology and Hydrogeology, 54(3).

18 (155-158) The modelling is undertaken within a closed system, how realistic do the authors believe this to be? Even when relatively shallow workings (<100 m) are considered there is often a hydraulic connection to deeper levels where mining (as evidence through mine plans and/or mine survey reports) is often more widespread (e.g., Northumberland and much of the Central Coal Field in the Midland Valley of Scotland).

19 (168-176) In this section you discuss the inter-stratification of coal bearing successions, which I agree is an important factor that will affect the thermal modelling. However, I am unsure about is the applicability of lumping the non-coal successions into a CRS with such high porosity into the 3D modelling. Even sandstones within many UK Carboniferous successions are 'tight' and require fracture flow to enable the extraction of water from these successions. Additionally, several of the paleosols that make up the succession have very low porosity and permeability values, along with high organic content that may act to extend the thermal blanket effect you observe within the coal seam. I think the rationale behind these numbers requires further elaboration and comparison to true successions to give the reader confidence that sensible values are being taken forward into the modelling.

20 (190) I am unaware of examples where thick coals, which themselves are very localised in the UK, where worked in the way in which Model 2 was ran. Due to these seams typically forming in localised locations related to structures (e.g., at throw maximums along syn-depositional faults) the thickness was not laterally extensive and from my knowledge of the mining records and literature were either a) worked locally using stacked stripped mining or b) worked from the base of the seam with the upper part of the seam was supported with pit props (locally the High Main Seam in Northumberland was worked this was near the S and Z splits, County Durham). Due to the unusual lay out or workings in the centre of the seam, I think the rationale behind this requires further explanation, although an unintended consequence of this is that the modelling approach would be similar to seams surrounded by organic rich paleo sols and shales.

21 (215-224) I really like this comparison as it provides a 'value' to such schemes that is so often lacking when communicating with investors/stake holders during the feasibility phase. Would you find the same level of year on year improvement if an open system was modelling (e.g., with variable boundary conditions). This may be out of scope of the current study, however, the limitation should be stated in the results to ensure robust communication with non-technical partners.

22 (241) Many abandoned mines require constant pumping to maintain water levels, particularly where daylights are below pre-mining GW levels. This suggests that these systems have substantial levels of groundwater flow, which would increase the importance of pore-water contact for the transfer of heat. Providing some mining data of schemes that are in the quasi-stationary state of groundwater conditions would help support the modelling approach and demonstrate the applicability to true mine-water systems.

23 (245) The worked thickness matching the thickness of the coal is the most common occurrence in pillar and stall mining methods, so the improved performance of model A over B is positive and should be highlighted.

23 (248) A drawback of targeting limestones is that they often act as regional groundwater aquifers and therefore would be unlikely to have static groundwater conditions.

24 (261-3) How do the authors suggest this would be minimised to increase the efficiency? Has any of the currently active schemes altered their cycles in response to similar efficiency concerns?

25 (Section 3.3) This is a standout section of the manuscript and could be very useful during discussions with investors – however, the caveats need to be more clearly laid out.

26 (288-290) It is promising that the efficiency of the modelled system increases in efficiency through time, however, the modelled rock-mass is very small compared to working that would be targeted for these schemes. I am also not convinced that it would remain a closed system without communication with regional groundwater flow patterns, which would in turn decrease the efficiency of the system.

27 (318) I agree that the system is highly susceptible to geological, as well as probable anthropogenic, conditions of the site. The rock model used for this modelling is by necessity simplified, however, the presence and percentage of shale (typically 40–60% of UK Coal Measures) in the system appears to have been ignored in the set-up of the model. As a minimum I believe a section on geological limitations and comparison to true mined sections needs to be added to provide context for the modelling that has been undertaken.

28 (332–336) How would the quoted values for time differ in a system that is 'scheme scale', which would often look to utilise one or more worked level with the volume of extracted coal an order of magnitude higher than the modelled volume. Additionally, whilst the geometry is a 'typical' pillar and stall layout, as pointed out by Bell & Bruyn 1999 this can vary due to ground conditions. Most workings I have worked with have shown large differences either through time as working practices varied (e.g., higher extraction rations could be maintained due to better pit-prop technology) or in the vicinity to geological structure (rolls and faults). Quoting efficiency values and the number of years before a scheme reaches the 'value' of mined coal with modelled rock volumes so different to the true case is a major limitation and should be discussed. I still believe the modelling adds to the community and is a good initial study, however, needs to be placed within the context of planned and ongoing mine water schemes. To this note, adding improved rock models for modelling should be considered for future modelling.

29 (469–471 – Fig 1 Caption) What does electricity demand add to this figure that is not shown by the heat demand? Additionally, electricity use due to lighting will contribute to the electricity demand making the link a little less easy to deduce.

Have you altered the graph at all? 'Made by Sansom (2014)' raises potential copyright issues. If you remade with the raw data it is better to say '(after Sansom, 2014)'

Further, to demonstrate the usefulness of 6-month cold-refill/heat extraction cycles you could add where this would be undertaken onto this plot.

30 (Table 1) At the very low pumping rates would you have to consider the effect of scaling on the system? This could be particularly importance in high ochre mines.

31 (Table 2) What is the rationale behind choosing these values? Are they based on rock properties from coal bearing sequences, and if so appear to differ from values I am used to, particularly for coal. Additionally, values for the CRS can be highly variable (clay-rich seat earth vs channelised sandstone).

32 (Figure 3) What is the purpose of the inset in the bottom right of this figure? Adding a scale onto the depth and horizontal extent of the model would aid the reader, what does the 'Cooling' on the left panel (6-Month Heat Storage) refer to, or is this relating to the graph? The purpose of the graph needs to be clearly stated in the figure caption, with figure 3 and 4 potentially being able to be combined to show the rational and conceptual set up of the model.

33 (Figure 5) How is the volume of water calculated?

Using the following calculation, I get 2304 m3, have you included the volume of water in the shaft?

Volume of pillars = (12 x 12 x 1) x 9 = 1296
Volume of workings = 60 x 60 x 1 = 3600
Extracted volume = 3600-1296 = 2304

Additionally, this is on the very high end for the extraction ration of pillar and stall workings (e = 0.64). Between 0.35-0.7 is the range, with the majority of workings around e = 0.5.

34 (Figure 7) At what level are the temperate maps taken? It was not clear what situations they were shown based on the figure and figure captions alone. A fuller figure caption and/or inset added onto the figure would clarify this.

35 (Figure 8) It is difficult to differentiate the lines, particularly for Model A. This is particularly bad when the manuscript is printed. I suggest dashing the lines like Model B.

36 (Figure 10) This figure is quite useful for communicating the heat that remains in the system after heat extraction, however, adding an additional time step half-way through extraction and storage would provide a powerful visual of how the system evolves.

QUALITY ASSESSMENT

Q 6	Originality	▮ ▮ ▮ ▮ ▯
Q 7	Rigor	▮ ▮ ▮ ▯ ▯
Q 8	Significance to the field	▮ ▮ ▮ ▮ ▯
Q 9	Interest to a general audience	▮ ▮ ▮ ▮ ▯
Q 10	Quality of the writing	▮ ▮ ▮ ▯ ▯
Q 11	Overall quality of the study	▮ ▮ ▮ ▯ ▯

REVISION LEVEL

Q 12 — **What is the level of revision required based on your comments:**

Moderate revisions.