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An Economic Model for a Thermal Energy Network

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ABSTRACT

Thermal energy networks (TENs), also known as fifth-generation district energy systems, provide a viable method of efficiently integrating electricity into heating and cooling in residential and commercial districts. In these systems, buildings are connected to an ambient-temperature loop via heat pumps and can exchange energy with the loop for heating or cooling. TENs have not been extensively implemented in the United States and thus require further studying and modeling for future optimization. Furthermore, previous modeling work has focused on technical performance and thermodynamics, while little work has been done on the economic analysis of these systems. NREL has developed a reduced-order model simulating the technical performance of TENs, specifically using geothermal boreholes as the thermal source. Our objective through this paper is to present a partner model that simulates a techno-economic analysis of a TEN to determine thermal energy pricing for customers. This model is more general than the technical performance model and could be adapted to take other thermal sources. The model groups the following technical parameters: customer heating and cooling loads as thermal energy produced by the system, and the electricity consumed by the system as annual operational expense in a calculation of the levelized cost of 'x' energy flow (LCOx). The model takes in financial parameters including the price of electricity, target internal rate of return, tax, insurance, debt repayment, and incentives. The economic metrics the model outputs include the LCOx, net present value of the technology, and thermal energy payments for customers as a function of time. This LCOx economic model will eventually be leveraged to further optimize the technical and economic performance of TENs by both scientists and industry partners.

1. INTRODUCTION

In the United States, residential and commercial buildings rely heavily on natural gas and electricity for heating. As low-cost renewable electricity generation grows, efficient integration of these energy sources allows one to transition away from natural gas as a sole heating source, adding resiliency to potential energy supplies. Thermal energy networks (TENs), also known as fifth-generation district energy systems in this instance, provide a viable method to utilize low-cost electricity to reduce carbon emissions from fossil heating and cooling loads. In a TEN, buildings in a district are connected to an ambient-temperature loop; this allows them to share thermal loads by using heat pumps to interface with the circulating energy (Buffa et al., 2019). Buildings can pull in energy from the loop for heating or release heat into the loop for cooling. This heat pump process reduces the need for on-site gas or electric-resistance heaters. Using geothermal heat pumps (rather than air-source heat pumps) provides further benefits in reducing both power costs and electricity consumption (Liu et al., 2023). When using geothermal boreholes, specifically, as the thermal source, these systems are called geothermal networks. Case studies of existing TEN applications—such as in Colorado Mesa University, Colorado, and Whisper Valley, Texas—provide promising results; these results include greater energy grid efficiency and system resiliency (Oh and Beckers, 2023; Business Wire, 2022).

The Learning from the Ground Up (LeGUp) project led by the Home Energy Efficiency Team (HEET) seeks to study the first utility-scale pilot geothermal networks installed in Massachusetts in the northeastern United States (HEET 2024). These installations include ambient-temperature loops of a single pipe network, which connect buildings, heat pumps at each building, and geothermal borehole fields for further heat exchange capacity. For these studies, the National Renewable Energy Laboratory (NREL) is helping to develop an open-source digital model of TENs. The model will be used to inform the optimization of designing and operating fifth-generation geothermal district energy systems, in both the technical and economic aspects. Previously, a generalized reduced-order model (ROM) was developed by NREL as part of HEET's LeGUp project to simulate technical performance (Simpson and Zhu, 2024). The primary improvement to this model is the addition of techno-economic assessment capability, which is the focus of this paper. The technoeconomic model would be added to the ROM and is called HEATNETS.

While there are existing models that simulate the economic performance of energy-generating systems, such as those provided by NREL's System Advisor Model™ (SAM™), those models typically evaluate the energy flows in a system independently (NREL, 2018). Heating is considered separately from cooling, which is not representative of the energy flow in a TEN, and the electricity load of operating the TEN is not supported. In a TEN, buildings as users operate as "prosumers"—producers and consumers—meaning that they can both take thermal energy from and contribute energy to the networked system. This creates a circularity of energy flow in a TEN, with heating and cooling loads being shared between users. Thus, an economic model that considers the different types of energy (heating and cooling shared between users and electricity required to operate the system) more holistically, with users modeled as prosumers of thermal energy, is necessary to fully represent a TEN.

2. MODEL METHODOLOGY

2.1 General Framework

A cash-flow model was written in Python 3 to simulate the economic performance of a TEN over its lifetime. This model was heavily based on the power purchase agreement single-owner utility financial model developed for SAM (version 2023.12.17; NREL, 2018). However, SAM's economic simulations goal to price electricity flows. When developing the economic model for TENs, it was important to maintain the key principle of accounting for multiple types of energy flow. Three types of energy flow were ultimately considered: heating, cooling, and electricity. To achieve a holistic consideration of all three energy flows, heating and cooling were grouped together as one energy to be priced, and electricity consumption was considered as part of the operating expenses in annual calculations. It should be noted that this electricity cost was calculated separately from the base operation and maintenance costs. This distinction was made to eventually make it easier to implement time-of-day factors (i.e., peak or off-peak factors) applied to electricity costs in the future as well as account for an escalation factor without impacting the base operation and maintenance costs.

The model takes in a set of financial and technical parameters. The basic financial parameters include the project's target internal rate of return (IRR)— which is the minimum required IRR—target IRR year, capital costs of installation, operation and maintenance costs of running the system (i.e., annual routine maintenance), price of electricity charged while operating the system, inflation rate, discount rate, and project lifetime. Users must also input additional pricing factors for the thermal and electricity energy flows, including cost escalation rates and time-of-delivery factor schedules. Users then have the option of including other financial parameters to raise the complexity of their simulation, including state and federal tax, insurance, project term debt, state and federal tax incentives, state and federal tax credits, and tax depreciation with a default 5-year modified accelerated cost recovery system (MACRS) schedule.

The technical parameters include the thermal loads (kWh_{th}), of each building in the system, as well as the electricity consumption loads (kWh_e) of each operating component in the system, both utility and non-utility. The physics-based ROM part of HEATNETS can be used to generate the technical parameters needed to run the economic model. However, the economic model can also be run separately, if the specifications of the proposed system are known.

The input parameters include technology-specific technical parameters (such as electricity consumed running the system and thermal loads of buildings on the loop) that are unique to TENs, which are not within the capabilities of other software applications. Using the input parameters, the economic model calculates a series of output economic metrics. These economic metrics include some terms defined within this paper, such as the levelized cost of "x" energy flow (LCOx) and the thermal energy price (TEP), as well as the annual, monthly, and daily bill for each customer on the loop in Year 1. The x in LCOx (in the case of a TEN) uniquely represents net heating and cooling, with electricity consumption considered as an operational expense. The TEP metric refers to the calculated base price in Year 1 of the heating and cooling energy. This is similar to the power purchase agreement output in SAM when a target IRR is specified. Other standard economic metrics are also output, such as the ending IRR and the net present value (NPV). The economic model also provides thermal energy payment estimates for each building in the system by time step (annually, monthly, and daily). The program flow of the economic model is summarized in Figure 1:

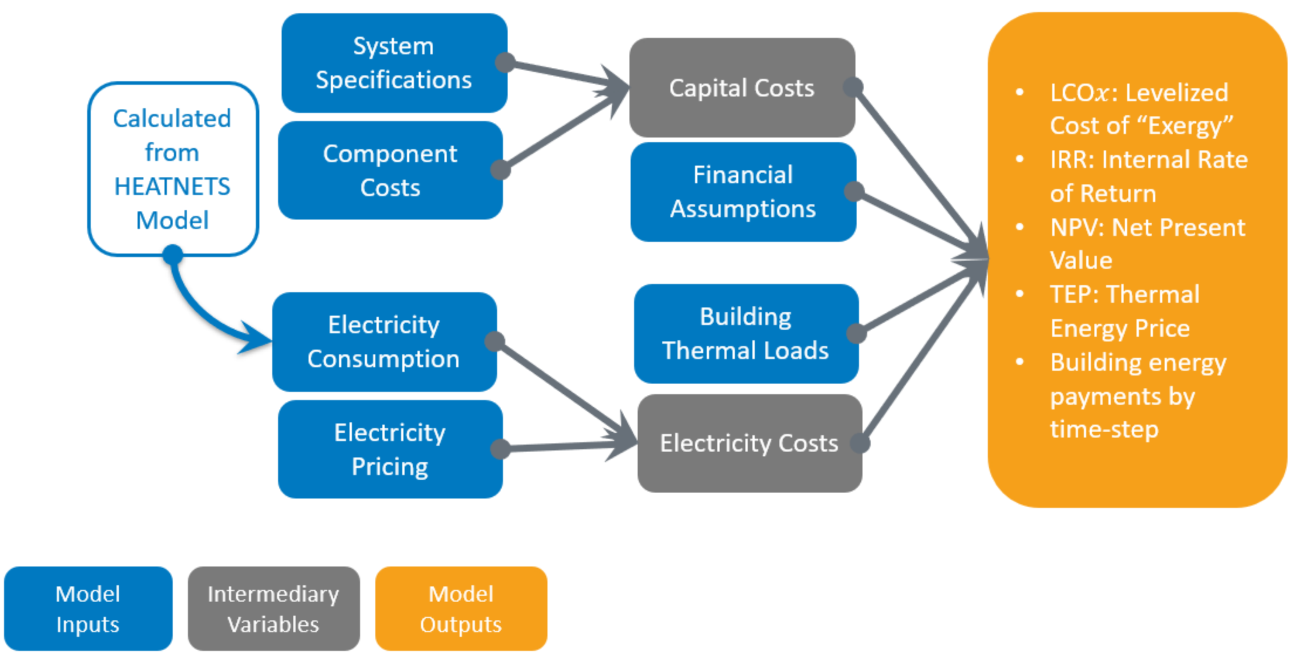

Figure 1: Economic model flow denoting financial and technical model inputs feeding into model outputs.

It should be noted that the capital costs are currently a single input field in the economic model. As more industry data are obtained on the costing of system components, the capital cost input will eventually be refined so that the model will internally calculate the capital costs from the system specifications. It should also be noted that the electricity required to run the system (annually) was included in a lumped annual operating and maintenance costs calculation. The electricity costs to run the system are calculated separately from the annual operation and maintenance costs and are added to the annual costs to create a "lumped cost," as in Equation 1:

$$Annual\ O\&M = \sum_{n=1}^{N} base\ O\&M * (1 + inf + esc\ for\ O\&M)^{n-1} + annual\ elec * (1 + inf + esc\ for\ elec)^{n-1} \tag{1}$$

where *O&M, elec, inf, esc, n, and N* are operation and maintenance costs, electricity costs, inflation rate, escalation rate, year, and project lifetime (years), respectively. An escalation rate for base O&M, and electricity price, can be assigned as separate user inputs under the financial parameters.

There are several assumptions within the model. It is assumed that a single owner of the system pays for the electricity consumption of both utility and non-utility components. For example, not only does the single owner pay for the electricity consumption of the circulation pumps around the ambient-temperature loop, but they also pay for the electricity consumption of the heat pumps at each residential and commercial building. In the future, a control mechanism will be implemented in the model to allow for flexibility to subdivide payment options to account for whether the consumer heat pump electrical loads are included as system costs. Another assumption is in how the model calculates the heating and cooling energy generated every year. Currently, this total energy is calculated from the building thermal loads as the net heating and cooling energy, where heating is a positive value and cooling is a negative value. It is also assumed that heating and cooling will be priced at the same rate.

2.2 After-Tax-Cash-Flow Calculation

A key aspect of simulating economic performance is calculating the system's cash flow over its lifetime. After-tax cash flow (ATCF) is calculated in Equation 2:

$$ATCF = Revenue - Operating\ Expenses - Debt\ Payment - State\ and\ Federal\ Taxes + Incentives \tag{2}$$

The specifics for calculating debt payment, state and federal taxes, and incentives were modeled after SAM's internal financial calculations. The current debt payment capabilities align with SAM's debt percent model, with fixed principal or equal payments. To calculate revenue, the pricing of the energy generated must be established. The revenue is calculated from three things: the thermal energy price that is required to make-up all costs over the lifetime of the project, the escalation rate applied to this thermal energy price, and the thermal loads. In the economic model, this variable is represented by the TEP. The TEP is a non-specifiable variable that is the thermal energy price corresponding to the user-specified target IRR and fixed financial metrics input by the user.

The equations for the calculation of the levelized output metrics for TEP and cost of electricity (LTEP and LCOx, respectively) are listed in Equations 3–6:

$$LTEP_{real} = \frac{\sum_{n=1}^{N} \frac{Project\ Revenue_n}{(1+d_{nominal})^n}}{\sum_{n=1}^{N} \frac{Q_n}{(1+d_{real})^n}} \tag{3}$$

$$LTEP_{nominal} = \frac{\sum_{n=1}^{N} \frac{Project\ Revenue_n}{(1+d_{nominal})^n}}{\sum_{n=1}^{N} \frac{Q_n}{(1+d_{nominal})^n}} \tag{4}$$

$$LCOx_{real} = \frac{\sum_{n=1}^{N} \frac{Project\ Costs_n}{(1+d_{nominal})^n}}{\sum_{n=1}^{N} \frac{Q_n}{(1+d_{real})^n}} \tag{5}$$

$$LCOx_{nominal} = \frac{\sum_{n=1}^{N} \frac{Project\ Costs_n}{(1+d_{nominal})^n}}{\sum_{n=1}^{N} \frac{Q_n}{(1+d_{nominal})^n}} \tag{6}$$

where d and Q represent the discount rate and heating and cooling energy flow generated, respectively. Real output variables consider inflation, while nominal output variables do not.

As part of our model's financial inputs, the user must specify a target IRR and a target year to achieve this IRR by. The target IRR is defined as the discount rate at which the NPV equals 0, as shown in Equation 7:

$$NPV = \sum_{n=0}^{N} \frac{After\ Tax\ Cash\ Flow_n}{(1+IRR)^n} = 0 \tag{7}$$

Where NPV and IRR are the net present value of the project over the lifetime of the project (N), and the target internal rate of return to be achieved by the target year for an associated TEP, respectively.

To calculate the TEP that generates the revenue required to meet this target IRR, the economic model undergoes an iterative algorithm, as illustrated in Figure 2.

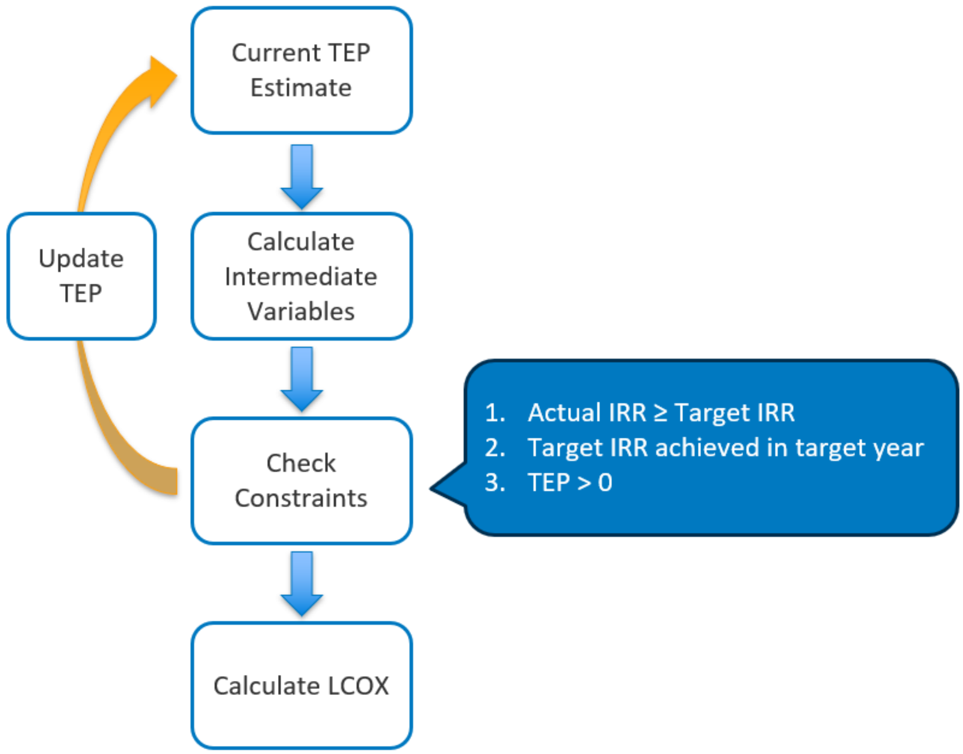

Figure 2: Iterative search algorithm for the thermal energy price (TEP), given a target internal rate of return (IRR) and a target year to achieve that IRR by.

After calculating the TEP for the system associated with the target IRR, the economic model can proceed to evaluate the system's after-tax cash flow and other related output economic metrics, such as the LTEP.

Calculations for the components of the after-tax cash flow (e.g. revenue, operating cost, debt payments) were based on and verified against the calculations made by SAM. This was done before the methods the model uses to handle the unique aspects of TENs were implemented. Numerous simulations were conducted in our economic model using its generic state, with a matching set of initial conditions (capital costs, operating costs, inflation rate, etc.) also input into SAM. The results of both models were then compared. When the difference between the generic economic model and SAM was sufficiently low, we incorporated any methods unique to TENs to create technology-specific inputs for the most recent version of the techno-economic model.

3. MODEL DEMONSTRATION

Sample model inputs were used to demonstrate the model's capabilities. These model inputs were not representative of an existing case study, as more analysis is needed to do a full simulation and interpretation of techno-economic results for an existing system. Technical inputs (for instance, number of buildings on the loop, the heating/cooling loads required by each building, the electricity required to run the system) were generated from the HEATNETS model developed by NREL for the simulation of TENs (Simpson and Zhu, 2024). The financial inputs for the following example simulated primarily use SAM and NREL's Renewable Energy Integration and Optimization (REopt®) techno-economic decision support platform defaults, rather than industry-verified data because industry-verified data are not yet available for TENs (Mishra et al., 2021; NREL, 2018). The electricity price used was the average U.S. price as of May 2024 of 12.6 cents/kWh (U.S. Energy Information Administration, 2024), and this price was assumed to be held constant over the project's lifetime. Thus, the following results are for the purpose of demonstrating model capabilities and do not accurately demonstrate industry expectations. The technical data input for electricity consumption and thermal loads was pulled from a ROM simulation of a geothermal network servicing a mix of residential and commercial buildings.

Table 3 shows the output economic metrics calculated for the example case. These are financial metrics that can be used to help predict profitability of a system or contextualize possible pricing for consumers. TEP denotes the thermal energy price required in year one to achieve the target IRR. LTEP denotes the levelized thermal energy price, and it represents the levelized revenue for the system over the project lifetime, accounting for any inflation in TEP each year. In addition to the TEP and LCOx metrics, another output variable is the minimum debt service recovery ratio (DSCR). DSCR is a financial metric that compares operating income to debt obligations, such that a higher DSCR is more favorable.

Table 3: Output economic metrics for the example case.

Metrics	**Value**
TEP price in Year 1 ($/kWh)	0.11
Nominal LTEP ($/kWh)	0.15
Real LTEP ($/kWh)	0.10
Nominal LCOx ($/kWh)	0.14
Real LCOx ($/kWh)	0.10
NPV ($)	163,134
IRR in target year (%)	5.0
IRR at end of project (%)	8.15
Minimum Debt Service Coverage Ratio	1.29

The economic model also outputs thermal energy payments for each building in the system based on its annual thermal energy consumption. Table 4 shows an example of this output for one residential building in the example case.

Table 4: Output economic metrics for example case (one residential building on a modeled loop).

Annual Energy Consumption (kWh)	**Annual Payment in Year 1** ($)	**Monthly Payment in Year 1** ($)	**Daily Payment in Year 1** ($)
12,417	2,635	219	7.22

The economic model can also run parametric studies to analyze the sensitivity of the system with respect to different financial variables. Figure 5 shows an example of one of these parametric studies conducted using the economic model, varying the federal investment tax credit (ITC) percentage to evaluate its effect on the TEP. With a 30% federal ITC applied, the thermal energy price that a customer may pay is reduced significantly from the initial price with no tax credit applied. Future work may consider the additional effects of varying tax credits and incentives on real case studies to reduce the thermal energy price that customers may pay.

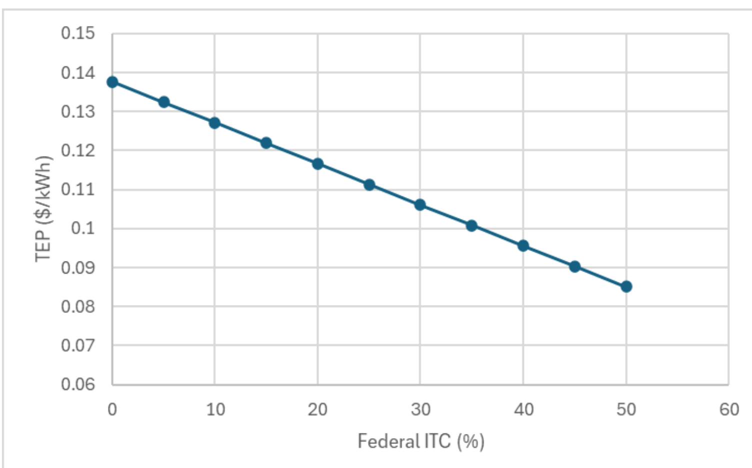

Figure 5: Effect of varying federal investment tax credit (ITC) percentage on the thermal energy price (TEP).

The nominal metrics report the TEP, LTEP, and LCOx with a fixed inflation rate applied to the electricity price and thermal energy price. The reason why the economic model for a TEN is unique is because the model accounts for the expense of electricity, outputs the thermal energy price associated with technology-specific loads of the TEN, and outputs the bill for each customer on the loop that they may be charged over the lifetime of the project annually, monthly, and daily in Year 1. This model differs from other software models such as

SAM because the model intakes the energy flows (electricity required to run all elements of the system, with or without heat pumps) and the building thermal loads unique to TENs.

4. CONCLUSIONS AND FUTURE WORK

The developed economic model serves as a valuable tool for studying and predicting the performance of TENs. By outputting key profit-estimating metrics such as NPV, IRR, and LCOx, it provides insights that are relevant for investors exploring this emerging industry. Additionally, the model outputs thermal energy payment estimates at annual, monthly, and daily time steps, enabling users to compare projected thermal energy prices with existing electricity and natural gas rates, making it useful for consumers as well. Overall, the model can assess the economic feasibility of TEN installations based on specific technical and financial inputs and can also assist in optimizing TEN designs for implementation.

Planned future work for the model described in this paper includes model validation, sensitivity studies, and further case studies to help better understand and improve TEN techno-economic analyses. More work will also be done to better integrate the technical model with the economic model within HEATNETS, so that the combined model can be used as a tool to optimize technical designs for economic outcomes.

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