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Integrating Geothermal Energy Use into Re-building American Infrastructure

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ABSTRACT

Given that a large portion of the United States' primary energy consumption goes into heating, cooling, and providing electricity to residential and commercial buildings, geothermal energy has significant potential to deliver and distribute both thermal and electrical energy on a community scale. Excluding a few exceptional cases in the U.S., the focus for development has been on producing electricity from high-grade hydrothermal systems located in various western U.S. states. By ignoring the potential to deliver thermal energy directly, a large portion of the U.S. geothermal resource is marginalized. In particular, lower grade, lower temperature hydrothermal and Enhanced Geothermal Systems (EGS) resources are more widespread and have sufficient temperatures (> 80ºC) that they are ideally suited for direct-use applications. By employing Geothermal District Heating (GDH) on a community scale, low grade hydrothermal and EGS in formations with poor permeability have the potential to supply a significant fraction of the thermal energy (temperatures < 125ºC) throughout the U.S., used for heating buildings, supplying hot water, and for lower temperature process heating. A key objective of our study is to characterize a number of important geothermal resource types ranging from conduction-dominated EGS to permeable sedimentary aquifers, as well as technical and economic factors that influence the levelized cost of delivering geothermal heat and/or electric power to a range of communities in the Eastern U.S. from lower grade resources (temperatures < 125ºC).

To demonstrate the level of deployment possible, we developed a regional model to evaluate the potential for GDH in the states of New York and Pennsylvania. A GDH network was simulated at each population center within the study region and the levelized cost of heat (LCOH) was estimated from GDH for each community. LCOHs were then compiled into a supply curve from which several conclusions were drawn.

Our evaluation revealed that geothermal resources have the potential to supply cost-effective energy for space and water heating in several New York and Pennsylvania communities in the near future. To realize wider deployment in NY, anticipated increases in conventional fuel prices, and/or more aggressive renewable energy policies and incentives along with modest improvements in EGS technology are needed to enable GDH to compete with other heating alternatives. In addition, creative implementation strategies would also help overcome the cost barriers that exist today for geothermal by focusing initially on developing the infrastructure needed for district heating and combined heat and power systems at a community scale. These district energy systems could be designed to initially utilize conventional fuels and waste biomass feedstocks and later transition to using geothermal energy as their primary energy source.

1. INTRODUCTION

Recent energy related and geopolitical events in Japan, the Middle East and North Africa have provided the wake-up calls we need to refocus our attention on energy security for the long term. Rational approaches are necessary and taking a closer look at how we use energy today is a good first step. For example, does it make sense to burn fuels at 1,800ºC or more to produce 100ºC water for a shower? Yet millions of people do this every day, in every city and town in the U.S. and around the world. By ignoring how energy is used to heat our homes and buildings and to provide hot water for everyday necessities like taking showers, cleaning clothes and cooking foods, we are missing opportunities to create a secure and sustainable energy future.

Our group has analyzed the thermal energy demand of the U.S. by evaluating published data from the last 40 years to see how much energy is consumed as a function of the actual utilization temperature. The result can be viewed as a "thermal spectrum" of current energy use as shown in Figure 1.

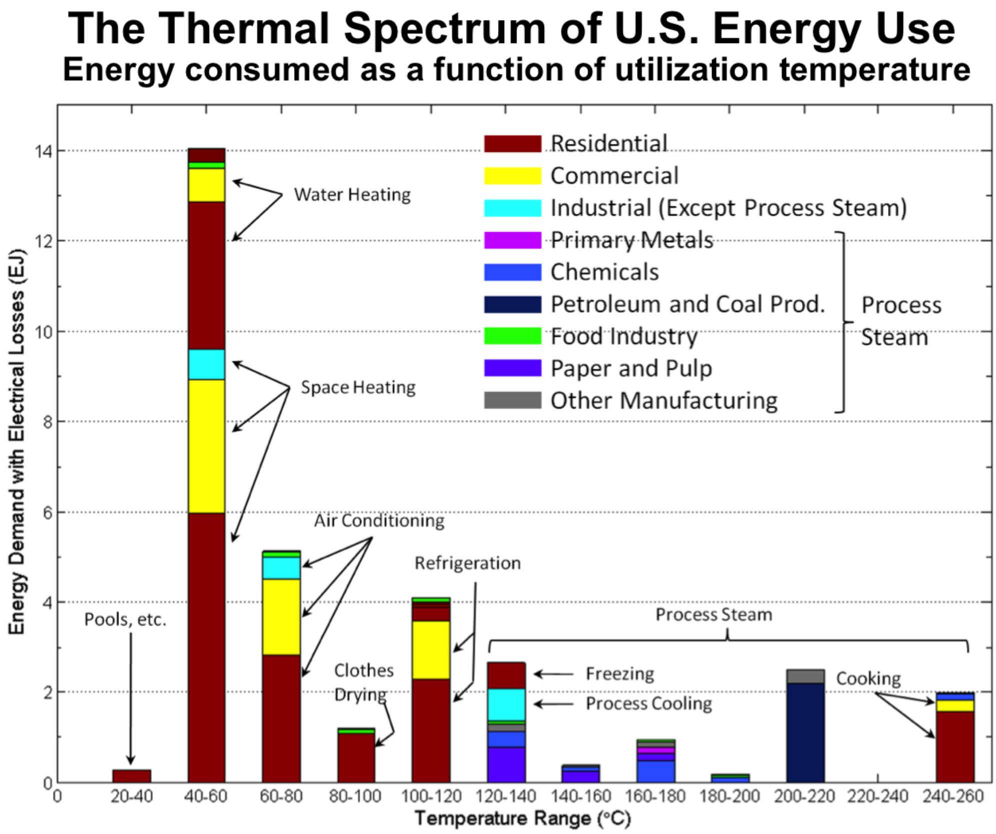


Figure 1. Estimated thermal energy consumed in America below 260°C (500°F). (From Fox et al., 2011 and Tester, 2011).

We found that about 25% of U.S. total primary energy is used at or below the boiling point of water (212ºF or 100ºC). Notably, most of this demand is met by burning three of our most valuable fuels – oil, propane, and natural gas – at much higher temperatures than needed, in hot water heaters and furnaces in virtually every American home or commercial building. The laws of thermodynamics tell us this use of high-temperature combustion energy is inherently wasteful. Quantitatively, this effect is described as a loss in work-producing potential resulting from a reduction in the availability or exergy of the energy source. A more efficient approach would be to first generate electricity from these hot combustion gases before they are used for heating applications at lower temperatures. This technique is used in co-generation plants found at Cornell University and many other large U.S. universities, which provide both heat and electric power in a distributed network.

Alternatively, finding thermal energy sources closer to the temperature of use would be a big improvement. By expanding our use of the abundant lower grade geothermal, solar thermal and waste heat resources in district heating and combined heat-and-power applications, we could significantly reduce our use of oil and gas. The technology is already here and has been in place for more than a century. The United States first developed a GDH system in Boise, Idaho in the late 1800s, but since then the U.S. has lagged far behind other countries, largely because we had abundant, low-cost oil and gas. In contrast, Iceland has utilized its high-grade geothermal resources to generate about 20% of its electric power and meet about 95% of its heating needs. In fact, Iceland has made a total transformation from complete dependence on imported fossil fuels to a renewable energy supply in less than 50 years.

U.S. presidents, congressional leaders and policy makers have emphasized the importance of developing more efficient, environmentally sustainable and secure ways to meet the country’s primary energy demands. They often advocate developing cleaner, indigenous renewable energy from wind and solar resources for electricity generation and biofuels from biomass as replacements to gasoline and diesel oil. While these changes are important, our results suggest that it will take much more than these efforts to transform America’s energy system.

We need to invest in developing the infrastructure to capture, transport and deliver low-grade thermal energy when and where it is needed. By utilizing our abundant indigenous renewable geothermal and solar energy resources at temperatures that closely match those required where the energy is actually used, we can maximize the exergetic efficiency of the energy transfer process.

For further information and documentation of our analysis of low temperature thermal energy use in the U.S., readers are referred to recent documentation, including “opinion” and “analysis” articles in *Energy and Environmental Science*, 2011 (Tester, 2011; Fox et al., 2013) and a comprehensive technical report available on the web at www.acsf.cornell.edu/2011Tester-LowTempEnergy.

2. APPLICATIONS OF LOW-ENTHALPY/LOW-TEMPERATURE GEOTHERMAL ENERGY

2.1 Geothermal Heat Pumps

Geothermal or ground-source heat pumps use the shallow ground as a heat source or sink to provide efficient heating and cooling at moderate temperatures. With a coefficient of performance (COP) on the order of 3 to 5 (units of heat transferred per unit of work input), geothermal heat pumps have a large energy savings potential. Typical applications are residential and commercial space and water heating. In the U.S. alone, more than 1 million units are currently installed with roughly 100,000 units added each year (Lund, 2011). Other promising applications include heating of swimming pools, fermentation and pasteurization in the food industry, heating and cooling of greenhouses, and cooling of data centers and cellular tower shelters. In our group, an experimental project is ongoing to study the energy, cost, and CO_2 savings of utilizing geothermal heat pumps to provide climate control for cellular tower shelters. Preliminary results show that geothermal heat pumps could be a more energy-efficient and cost-effective option than traditional wall-mounted air conditioning units (Beckers et al., 2014b).

2.2 Direct Use and Co-Generation in District and Distributed Systems

The opportunities for utilizing lower grade geothermal resources are greatly expanded when direct use and co-generation options are considered. As pointed out earlier, in the U.S about 25% (25 EJ out of 100 EJ) of the primary energy consumed per year is actually used at temperatures below 120ºC.

Nonetheless, there are large economic challenges for generating electricity given the low second law efficiencies of converting thermal energy into electric power at lower geofluid temperatures with thermal efficiencies about 10% or less. Direct use of thermal energy would be a more attractive alternative with utilization efficiencies of 90%. Thus, proximity to both thermal and electric demands would be more attractive for increasing the utilization of low grade geothermal energy. In addition, the incorporation of higher temperatures from combustion-based fossil or biomass systems or concentrating solar thermal using hybrid concepts to enhance the power producing potential of geothermal heat may also provide desirable options.

3. GEOTHERMAL RESOURCE ASSESSMENT

3.1 Context

Our work, which focused on New York State and Pennsylvania, was part of a larger U.S. geothermal resource assessment project that updates the 2004 and 2011 heat flow maps of the United States generated by the Geothermal Lab at Southern Methodist University (SMU) (Blackwell and Richards, 2004; Blackwell et al., 2011). Figure 2 shows the 2011 heat flow contours for the continental U.S. while Figure 3 provides an enlargement of the Northeastern region. Figure 4 provides an estimate of temperature at a depth of 5.5 km for the continental U.S. These earlier maps were based on a limited amount of data in the northeastern and mid-Atlantic regions of the country. Of immediate interest to our group was improving the geothermal resource assessment for the Ithaca, New York region, since Cornell University has made a commitment to lower its carbon footprint. Cornell's campus with 30,000 students, faculty and staff with a centralized energy supply system provides a representative community in the northeastern U.S. for district energy given its large thermal energy demand for heating and cooling of buildings. Based on earlier assessment data reported by the SMU Geothermal Laboratory in Dallas, Texas, we expect average geothermal gradients in the immediate Ithaca area to be considerably higher than other regions in New York. As early as 1975, an anomaly had been noted in heat flow and gradient maps of the region.

To increase the spatial resolution of geothermal resources in the New York and Pennsylvania region, our group contributed to the Geothermal Data Aggregation (GTDA) project. The GDTA project was led by SMU working in collaboration with Siemens Corporation, Bureau of Economic Geology at the University of Texas – Austin, Geothermal Resource Council (GRC), MLKay Technologies, Texas Tech University (TTU), and University of North Dakota. The mission of the GTDA project was to provide the National Geothermal Data System (NGDS) with legacy information from archived documents and current geothermal data from well logs.

The NGDS is operated by Boise State University in collaboration with SMU, U.S. Geological Survey (USGS), National Renewable Energy Laboratory (NREL), and the Association of American State Geologists (AASG) and is expected to serve as the central location for publicly available geothermal data, with the intent of mitigating much of the associated uncertainties with geothermal exploration and resource characterization (NGDS, 2012).

In this section we summarize two aspects of our work: 1) enhancements made to the geothermal dataset in New York and Pennsylvania by incorporating additional bottom-hole temperature (BHT) and geologic characterization, and 2) geothermal opportunities in deep sedimentary basins.

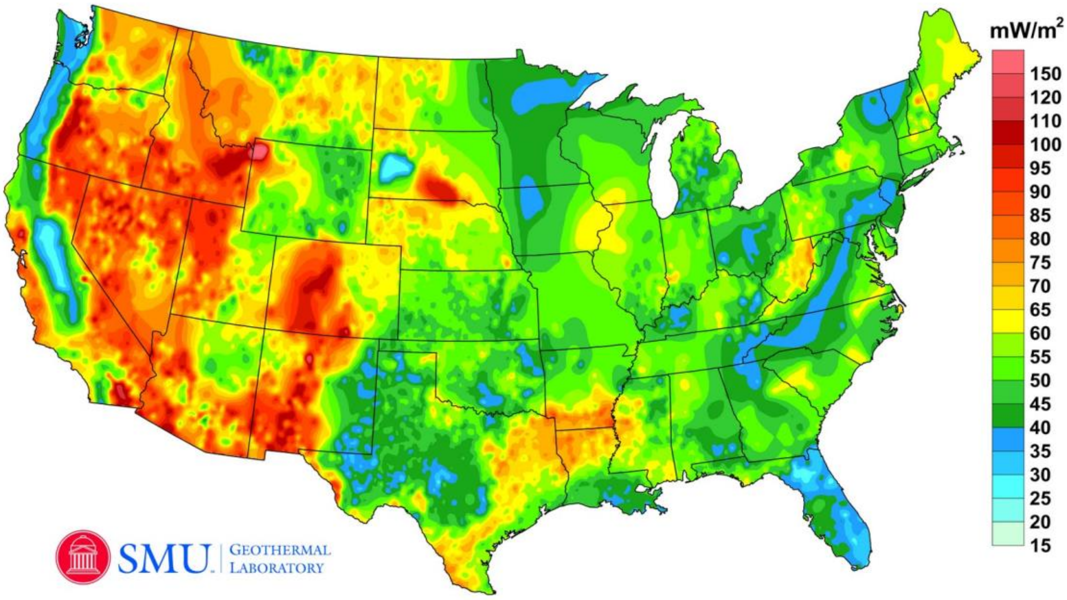


Figure 2. 2011 Geothermal Heat Flow Map of the Continental U.S (Blackwell et al., 2011).

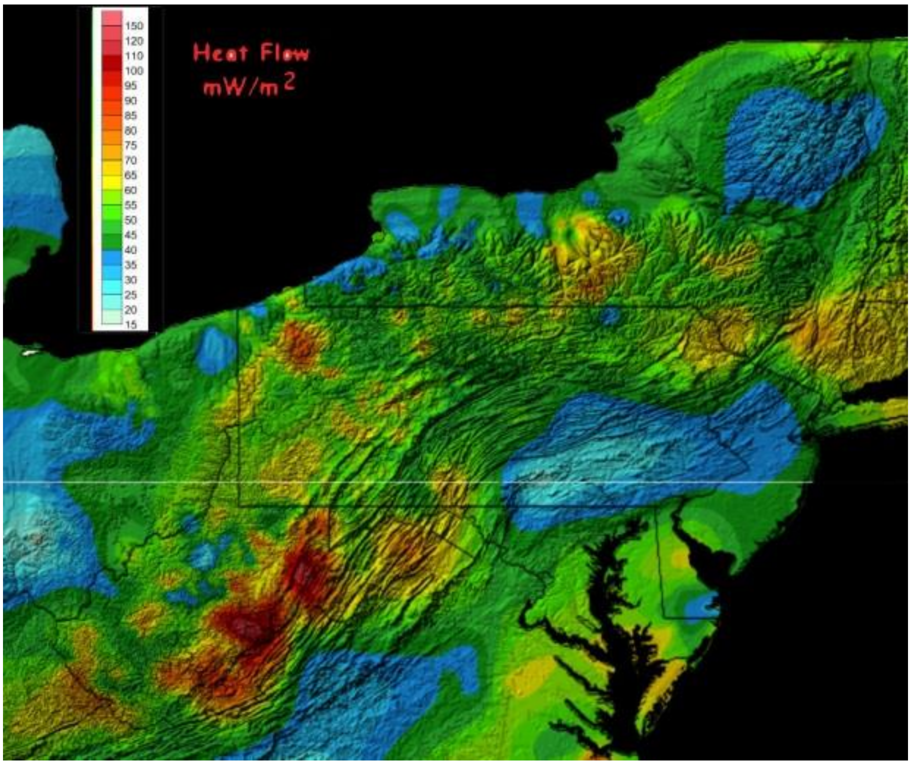


Figure 3. Enlargement of the 2011 heat flow map for Northeast region (Blackwell et al., 2011).

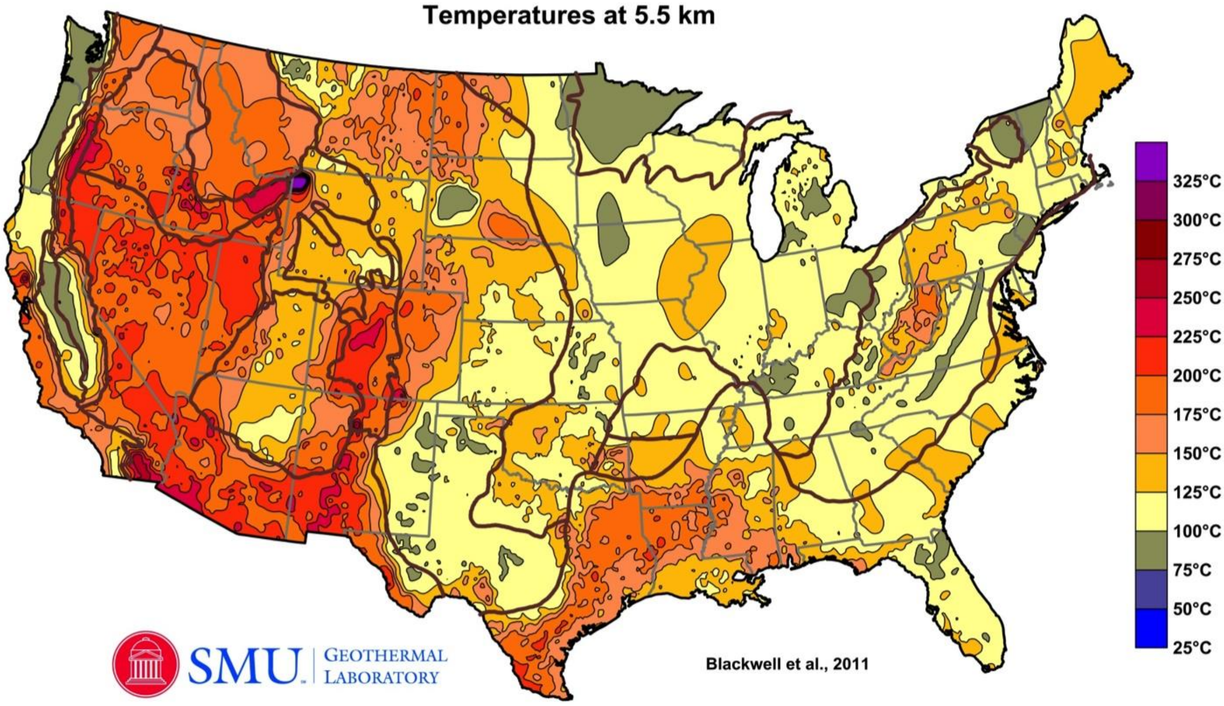


Figure 4. Predicted temperature at a depth of 5.5 km for the continental U.S. Provided by D. Blackwell and M. Richards, SMU, Dallas, TX, 2013.

3.2 Enhancements to Heat Flow and Geothermal Gradient Maps in New York and Pennsylvania

3.2.1 Data for the Northeast Region

A more extensive dataset of BHTs has become available in the last few years from extensive drilling into the Marcellus and other tight gas shales by the oil and gas industry in Central New York and Western Pennsylvania to depths ranging from about 1.7 to 5 km (4,000 to 15,000 feet). Preliminary analyses incorporating these additional data have been performed to develop the regional heat flow map and the maps of estimated temperatures at depths of 4.5 km and 6.5 km. These new data confirm that the geothermal resource under Ithaca is likely to have a higher temperature gradient than the surrounding region.

To provide proper regional context, we included two figures: Figure 5a: Regional and county of New York State and Pennsylvania, Figure 5b: Location of major cities in New York and Pennsylvania.

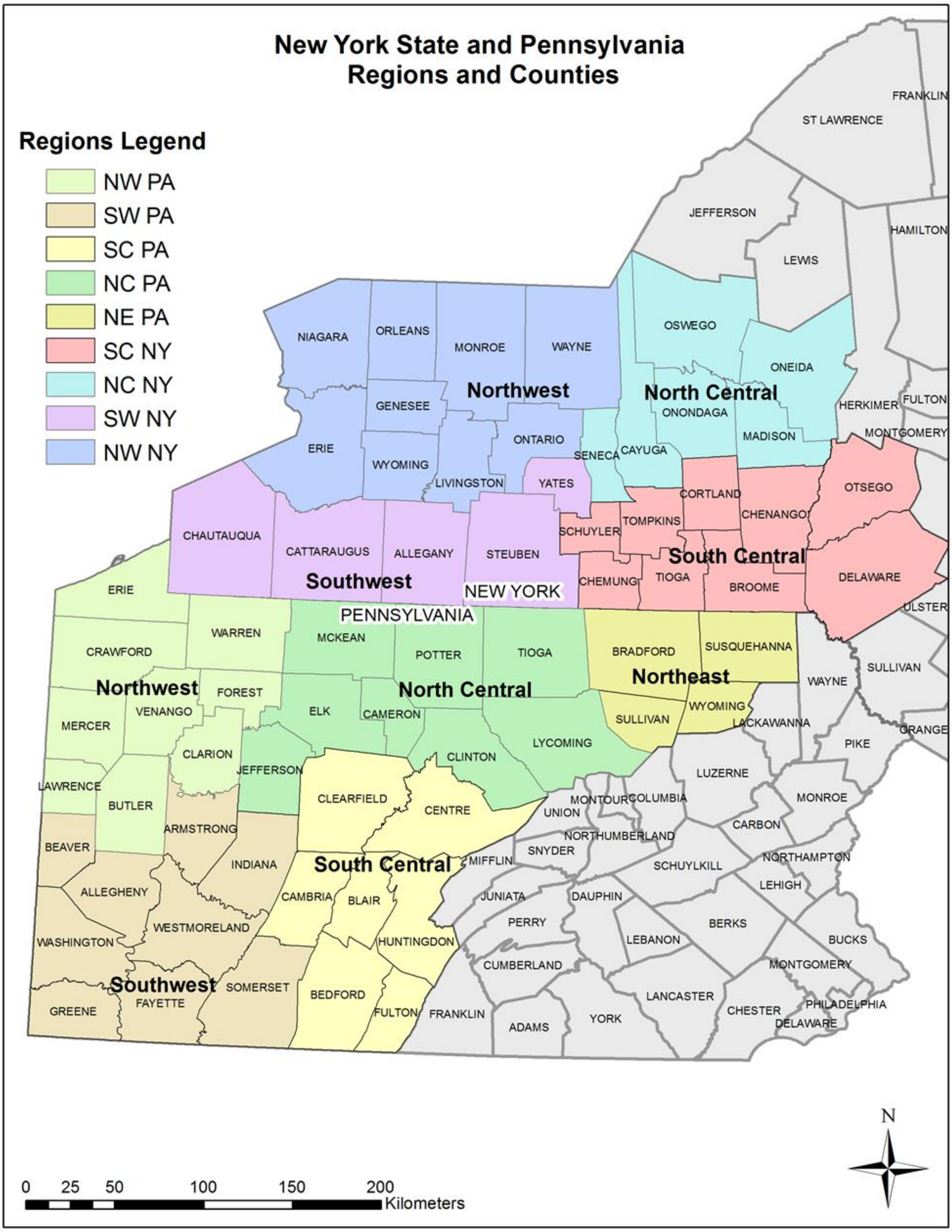


Figure 5a. New York and Pennsylvania State and county boundaries. Colored counties were considered in current study.

Figure 5b. Major cities and towns in New York State. Photo courtesy of NETState (http://www.netstate.com/).

3.2.2 Well Data Sources

Data in the form of oil and gas well logs and databases were collected from SMU, the New York State Museum (ESOGIS), the Pennsylvania Geological Survey (PA*IRIS system), and the New York State Department of Environmental Conservation (NYSDEC, 2011). The data extracted from archived and current well logs consisted of BHTs, log depths and/or true vertical depths (TVDs), location in the form of latitude and longitude, and American Petroleum Institute (API) numeric identifiers.

The resulting dataset contained 8,919 data points consisting of 7,969 wells, 745 of which had multiple readings at various depths. For the mapping of geothermal variables, when duplicate well entries were encountered as a result of multiple readings, the shallower measurements were dropped so that the dataset contained only one entry for each well. Geothermal variables of interest include geothermal gradient, surface heat flow, estimated temperature at depths of 3 km, 4.5 km, and 6 km, and estimated depth to the 80˚C and 150˚C isotherms.

3.2.3 Methodology

The set of maps developed for various geothermal variables include methodology presented by Tester et al. (2006), Blackwell et al. (2007), Shope et al. (2012), Stutz et al. (2012), Shope, E.N. (2012), and Stutz, G.R. (2012). The methods that assess the spatial variability and precision (standard errors) behind the estimated geothermal variables are presented by Aguirre et al. (2013) and Aguirre, G.A. (2014). A fully documented paper on the geothermal potential in the Appalachian Basin in New York and Pennsylvania will appear in the all-electronic journal, *Geospheres*, published by the Geological Society of America in late 2014 to early 2015. In addition, a summary of the *Geospheres* publication will be presented at the 2014 Geothermal Resource Council (GRC) annual meeting in Portland, Oregon.

3.2.4 Surface Heat Flow Estimates in the Appalachian Basin of New York and Pennsylvania

The estimates for surface heat flow are shown in Figure 6. From our analysis, the average estimated surface heat flow for New York State is 48.4 mW/m^2 and for Pennsylvania is 59.5 mW/m^2. The precision in the estimates (standard error) in areas of high data density is between 1.2–3.0 mW/m^2. Areas with modest data density display precision in the estimates for heat flow between 3.0–5.0 mW/m^2. Modest heat flows, greater than 55 mW/m^2 and with a precision within 2.0 mW/m^2, are recorded in central and southwestern New York, in the eastern border of the Appalachian Basin in Pennsylvania, and in western Pennsylvania.

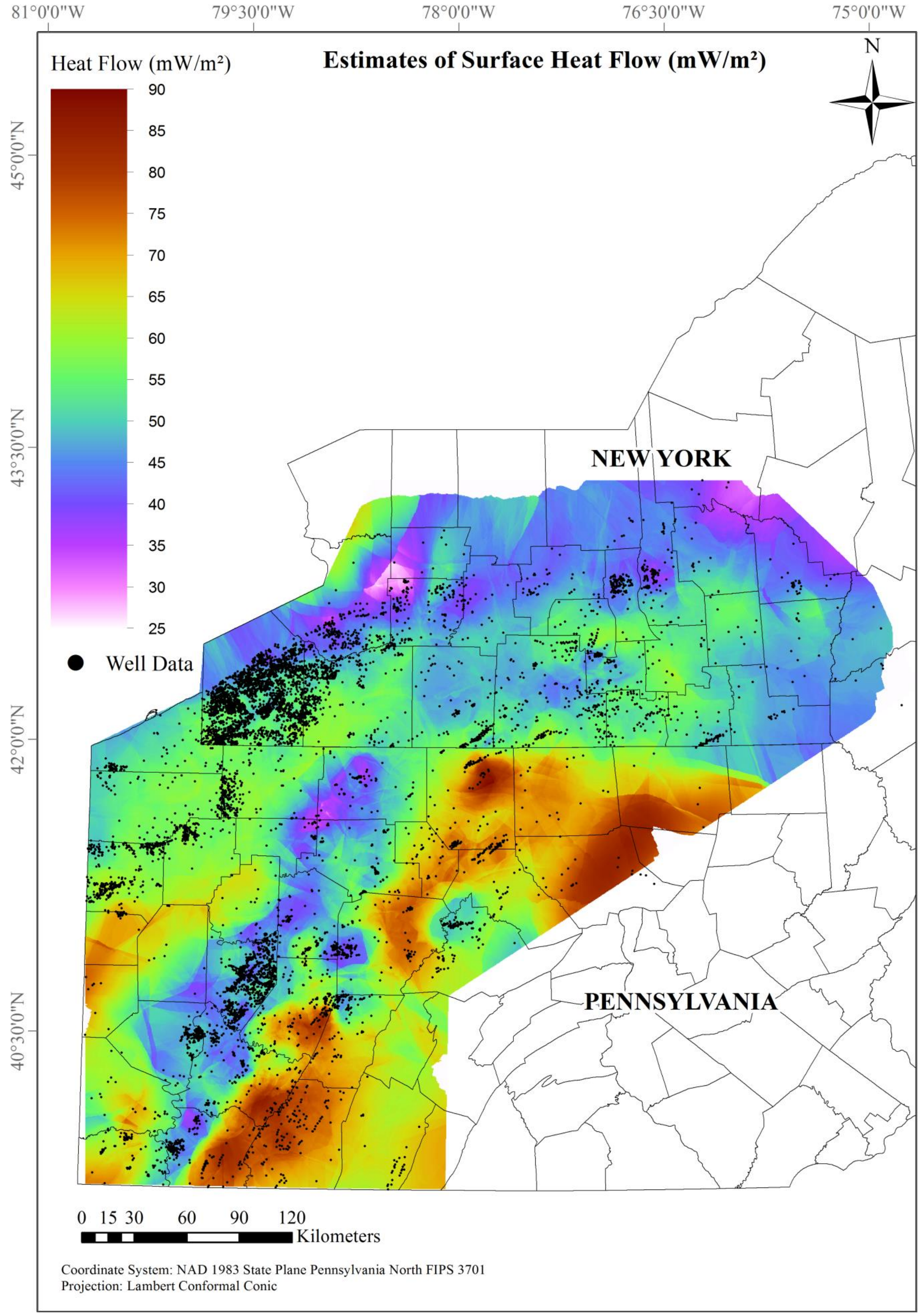


Figure 6. Estimates of surface heat flow (mW/m^2) for New York State and Pennsylvania, with individual well locations shown as black diamonds. Data sources: SMU, PA Geological Survey, NYS Museum, NYSDEC, 2011.

3.2.5 Estimates of Temperature-at-depth of 4.5 km in the Appalachian Basin of New York State and Pennsylvania

The estimates of temperature-at-depth of 4.5 km are shown in Figure 7. From our analysis, the average estimated temperature-at-depth of 4.5 km for New York State is 92.3ºC. The average estimated temperature-at-depth of 4.5 km in Pennsylvania is 118.3ºC. The precision in the estimation of any point (standard error) within the interpolated region was between 2–6ºC for areas with high data density. Areas with modest data density display precision in the estimates between 6–10ºC.

Areas that achieve temperatures greater than 80ºC are favorable for direct thermal use for district heating systems and/or combined heat and power. Several counties in central and southwestern New York report estimated temperatures at depth of 4.5 km that exceed 100ºC with a precision in the estimates within 4ºC. North central and south central Pennsylvania counties report estimated temperatures that exceed 140ºC with a precision within 4˚C.

3.2.6 Estimates of Temperature-at-depth of 6 km in the Appalachian Basin of New York State and Pennsylvania

The estimates of temperature-at-depth of 6 km are shown in Figure 8. From our analysis, the average estimated temperature-at-depth of 6 km for New York State is 115.5ºC. The average expected temperature-at-depth of 6 km in Pennsylvania is 149.4ºC. The precision in the estimation of any point within the interpolated region was between 2.5–7.0ºC for areas with high data density. Areas with modest data density display precision in the estimates between 7–12ºC.

Electric power generation from hot rocks and/or heated formation waters requires temperatures greater than 150ºC (Tester et al., 2005). Central New York reports estimated temperatures at depth of 6 km that exceed 130ºC with a precision in the estimates within 4ºC. In north central Pennsylvania, Potter County exceeds temperatures of 200ºC with a precision within 5ºC. Several north central and south central counties in Pennsylvania exceed temperatures of 180ºC with a precision within 4ºC. In western Pennsylvania, several counties estimate temperatures at 6 km that exceed 150ºC with a precision in the estimates within 6ºC.

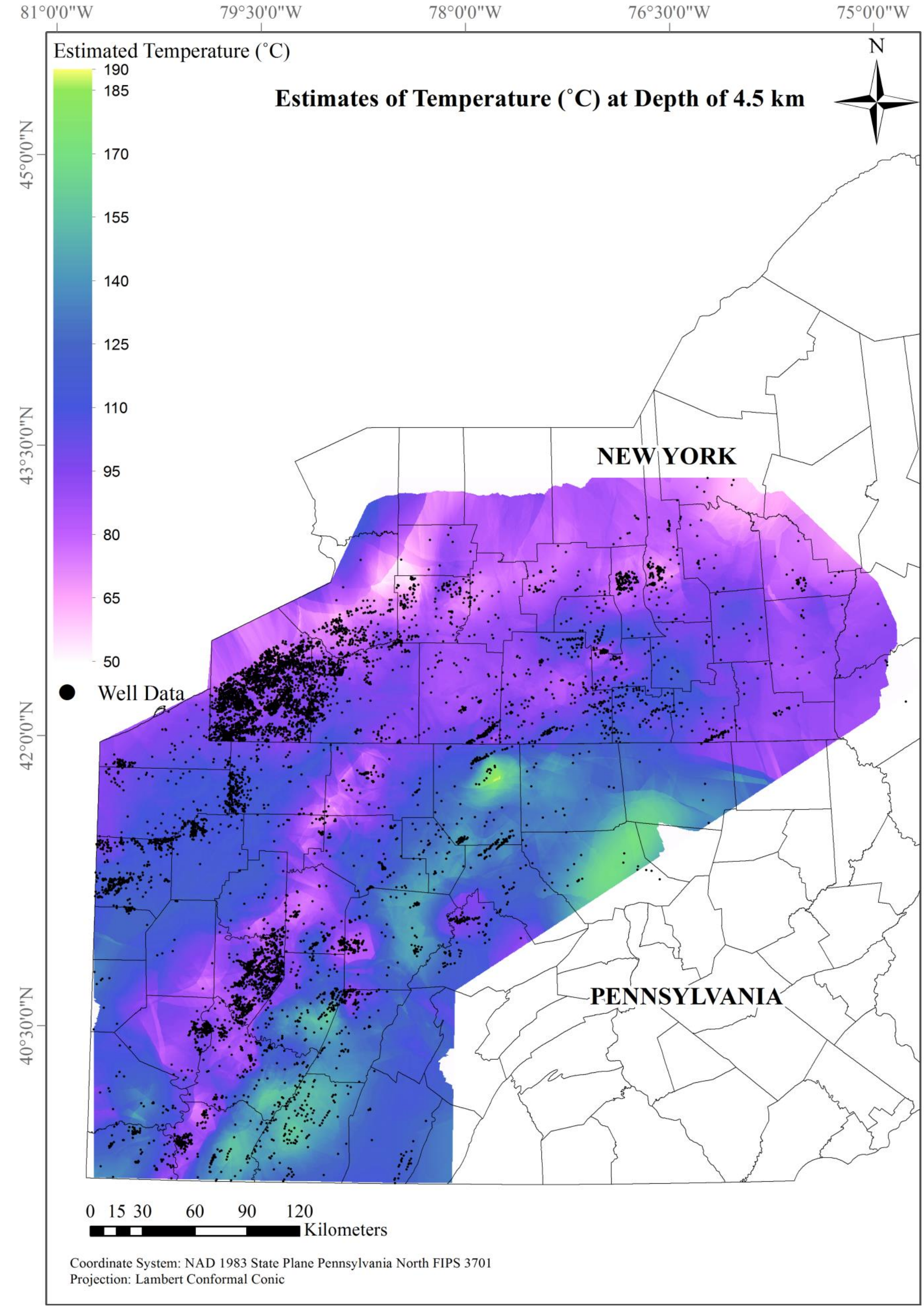


Figure 7. Estimates of temperature (ºC) at depth of 4.5 km for New York State and Pennsylvania, with individual well locations shown as black diamonds. Data sources: SMU, PA Geological Survey, NYS Museum, NYSDEC, 2011.

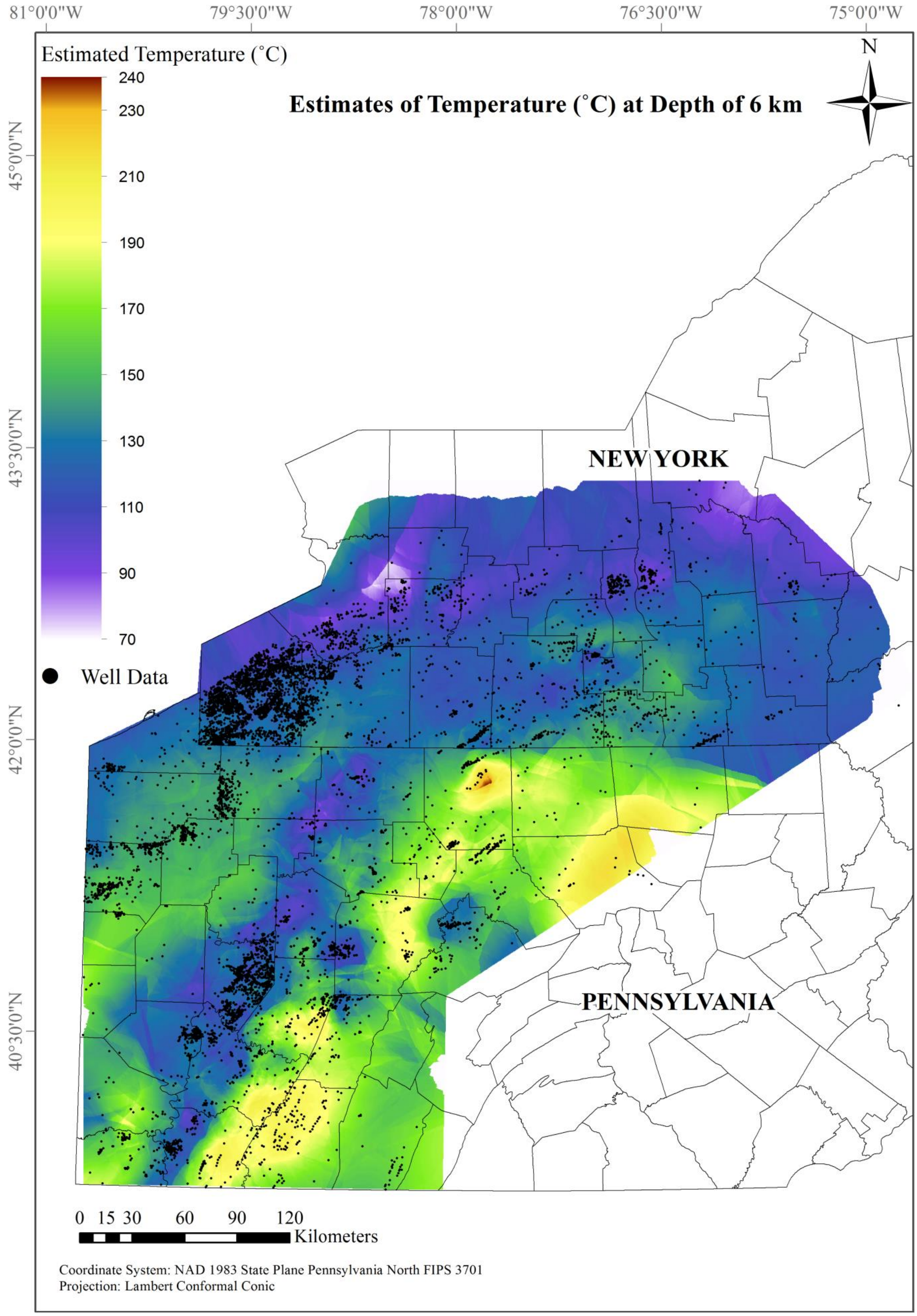


Figure 8. Estimates of temperature (ºC) at depth of 6 km for New York State and Pennsylvania, with individual well locations shown as black diamonds. Data sources: SMU, PA Geological Survey, NYS Museum, NYSDEC, 2011.

3.3. Geothermal Opportunities in Sedimentary Basins

Sedimentary basins present a promising near-term opportunity for GDH and other lower temperature direct-use geothermal heating for three primary reasons: 1) many sedimentary rocks have a lower thermal conductivity than crystalline rocks, therefore creating a 'thermal blanket' effect over the crust in certain regions, 2) many basins have been explored extensively by the oil and gas industry, providing an abundance of available data and pre-existing wells to reuse for reduced costs, and 3) certain sections of sedimentary basins tend to have higher porosities than crystalline basement, which increases chances for connected flow paths through the reservoir.

The densely populated northeastern U.S. has a substantial market for such applications, and is coincident with the geographic extent of the Appalachian Basin (See Figure 9a). Furthermore, Figure 4 shows higher temperatures at a depth of 5.5 km concurrent with the deepest portions of the Appalachian Basin, as compared to the surrounding areas. This consistency between high temperatures persisting in the basin demonstrates a potential thermal resource base for the region. There are 117 fossil-fuel-fired district energy systems in New York, Pennsylvania, and West Virginia with existing infrastructure in place that could be economically retrofitted for geothermal sources. Additional markets for direct use include the food processing and pulp and paper industries, all of which have a strong base in the region.

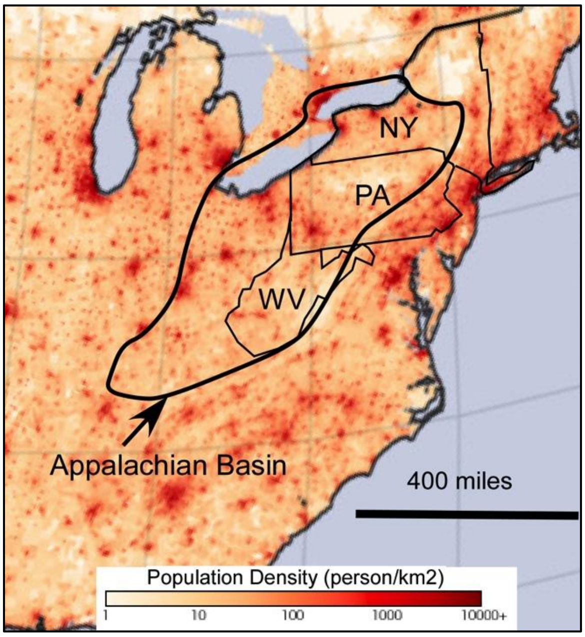


Figure 9a. Population density within the Appalachian Basin. Adapted from Robert Simmon, NASA, 2006.

The basin is rich in available geophysical and well data from previous and ongoing oil and gas exploration, specifically the New York, Pennsylvania and West Virginia segments. Additionally, recent studies generated a set of maps of thermal conditions based on many thousands of BHT data collected as incidental products of drilling for petroleum and natural gas (Blackwell et al., 2010; Stutz et al., 2012; Stutz 2012; Shope et al., 2012; Shope 2012). Those data have been compiled in the National Geothermal Database (NGDS) and in state databases and petroleum industry well logs and thermal data are available for thousands of locations in the regions.

The use of oil and gas reservoirs for coproduction of geothermal fluids is a promising concept, with the potential for reusing pre-existing wells, inherent connectivity of pore space, and the richness of reservoir data. Numerous studies have been conducted for potential oil and gas reservoirs in the Appalachian Basin (e.g., Roen and Walker, 1996; Patchen et al., 2006; Ryder, 2008). Most Appalachian Basin oil and gas plays at depths exceeding 3 km are fairly tight systems, some of them producing from natural fracture systems (Roen and Walker, 1996). The exceptions with high permeability represent much lower risk and warrant focus to develop a regional description of their occurrence.

For example, research on the utility of the Black River-Trenton hydrothermal dolomite gas fields of southern New York is currently ongoing at Cornell. For a few years in the early 2000's, these fields were the largest onshore gas producers in the U.S., and therefore a large amount of analysis and characterization has been done to understand their origin and quality. At present, the Quackenbush Hill Field in Chemung County, NY is of particular interest, with production from rocks whose porosity ranges from 5-10%, corresponding permeabilities from 20-100 mD (Marner, 2008), an average depth of 3 km to the formation of interest, an average temperature at depth of 80ºC, and very close proximity to the Elmira-Corning region (<5 km). Future research will explore the presence of these dolomite fields near Ithaca for potential use as a reservoir in a GDH system for Cornell, replacing the gas-fired co-generation system currently in placeby utilizing a hybrid geothermal biomass system.

Other promising depleted oil and gas reservoirs with potential for reuse as geothermal reservoirs warrant a close analysis: i) various formations in the fractured half-grabens of the Rome Trough, ii) the Knox Group sandstones and dolomites, iii) the lower Silurian Tuscarora Sandstone, iv) the lower Devonian Oriskany Sandstone (Kostelnik and Carter, 2009), and v) Devonian fractured shales and siltstones. The Cambrian sandstones (e.g., the Mt. Simon Sandstone, the Galway Sandstone) present interesting opportunities for larger-scale geothermal reservoirs if the right combination of depth and temperature coincide (US DOE 2012; Slater et al., 2008). Other options include potential saline aquifers, unmineable coal beds, and depleted oil and gas reservoirs, which have been geologically characterized for carbon sequestration (e.g., Carr et al., 2009; Kostelnik and Carter, 2009; Lewis et al., 2009; Tamulonis et al. 2012; 2014; Jordan et al., 2012).

Similar opportunities exist in other deep sedimentary basins across the U.S., such as the Gulf Coast and Michigan Basins (see Figure 9b).

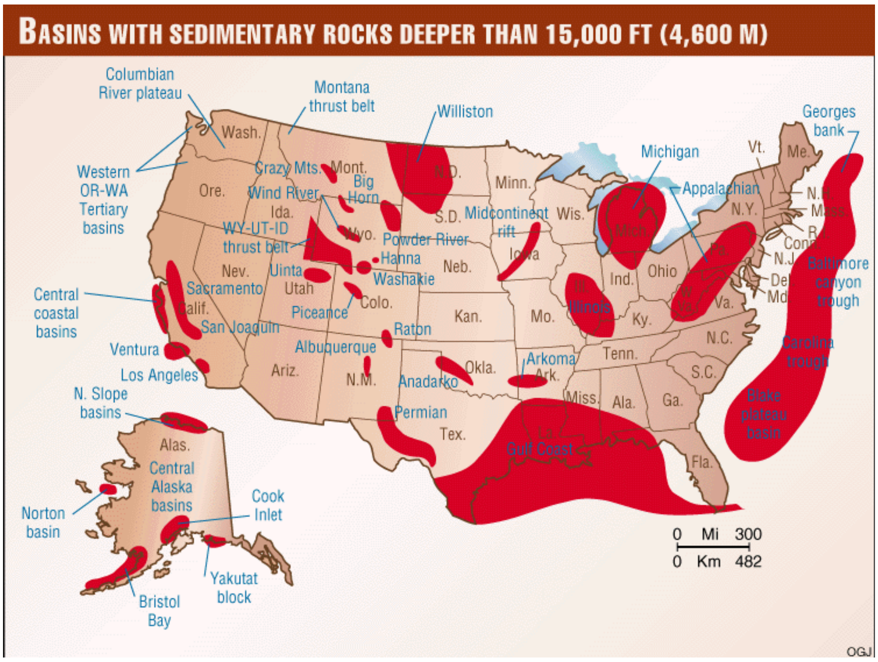


Figure 9b. Deep Sedimentary Basins in the U.S. with the potential for direct-use geothermal energy (from *Oil and Gas Journal*, 1998).

4. MODELING METHODS FOR EVALUATING SYSTEM FEASIBILITY

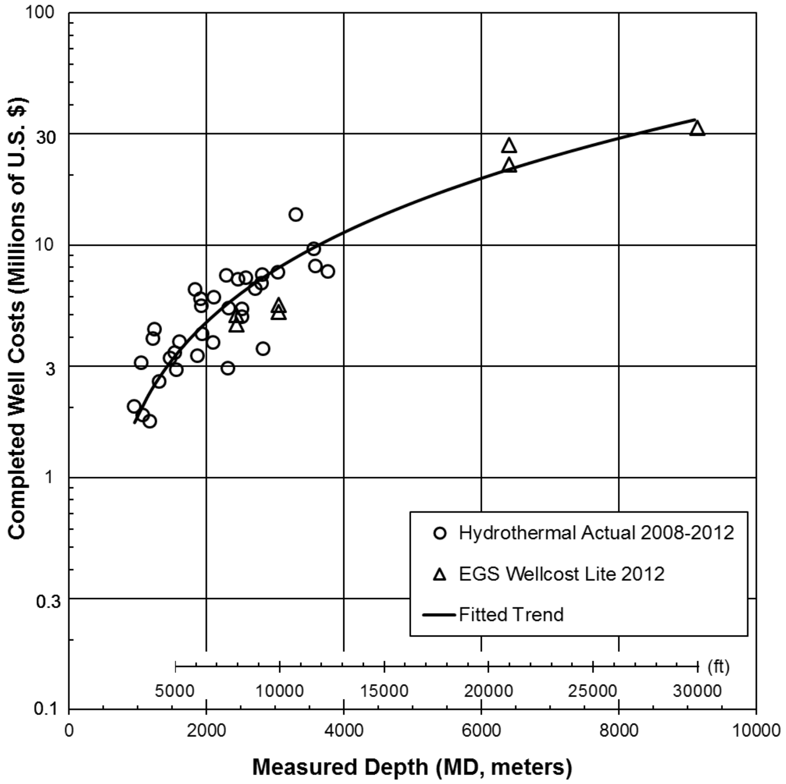
4.1 GEOPHIRES Model

In order to evaluate the feasibility of EGS, our group developed the software tool GEOPHIRES (GEOthermal energy for the Production of Heat and Electricity (“IR”) Economically Simulated). GEOPHIRES is a computer program that combines reservoir, wellbore, and power plant models with capital and operating cost correlations and levelized cost models to evaluate the technical and economic performance of EGS. It is the first software tool to simulate both electricity and direct-use heat and combined heat and power as end-use options. It includes the latest drilling costs correlations (Lukawski et al, 2014), and advanced power plant efficiency correlations based on Aspen Plus and MATLAB simulations. GEOPHIRES is described in detail in (Beckers et al., 2014). This study includes the levelized cost results for 18 EGS scenarios based on three different resource grades (low-, medium-, and high-grade resource corresponding to a geothermal gradient of 30, 50, and 70 ºC/km), three different levels of technological maturity (today's, mid-term, and commercially mature technology corresponding to a productivity of 30, 50, and 70 kg/s per production well and thermal drawdown rate of 2, 1.5, and 1 %), and two different end-uses (electricity and direct-use heat). The levelized cost results for the base-case scenario (medium-grade resource and mid-term technology) are 11 ¢/kWh$_e$ and 5 $/MMBTU (1.7 ¢/kWh$_{th}$), respectively. In Section 6, GEOPHIRES has been applied to the Cornell University campus to estimate the levelized cost of heat for a geothermal district heating system.

4.2 Drilling Costs

Our group examined the effect of drilling costs on the project economics by evaluating the current average drilling cost of geothermal wells. We inferred the cost of geothermal wells based on a dataset of 42 actual hydrothermal wells drilled between 2008 and 2013. In addition, we estimated the costs of 7 deep EGS wells using a predictive geothermal well cost model WellCost Lite (see Figure 10).

We found that despite the larger well diameters and the increased drilling complexity, geothermal wellbores have similar costs to oil and gas wells of the same depth. As shown in Figure 11, while shallow geothermal wells are typically cheaper than hydrocarbon wells, the predicted costs of deep EGS wells (>6000 m) are 10% lower than the average cost deep oil and gas wells. In addition, the historical cost escalation rates of geothermal wells were considerably lower compared to hydrocarbon wells.



1. Actual costs of hydrothermal wells are presented in nominal U.S.$ (2008-2012).
2. Costs of EGS wells are predicted using WellCost Lite model. EGS well costs are presented in 2012 U.S.$.
3. The average current costs of geothermal wells can be reasonably well approximated by a following equation: *Cost ($M) =* $1.72 * 10^{-7} * (MD)^2 + 2.3 * 10^{-3} * MD - 0.62$

Figure 10. Actual drilling costs for hydrothermal wells compared to EGS Wellcost Lite predicted costs.

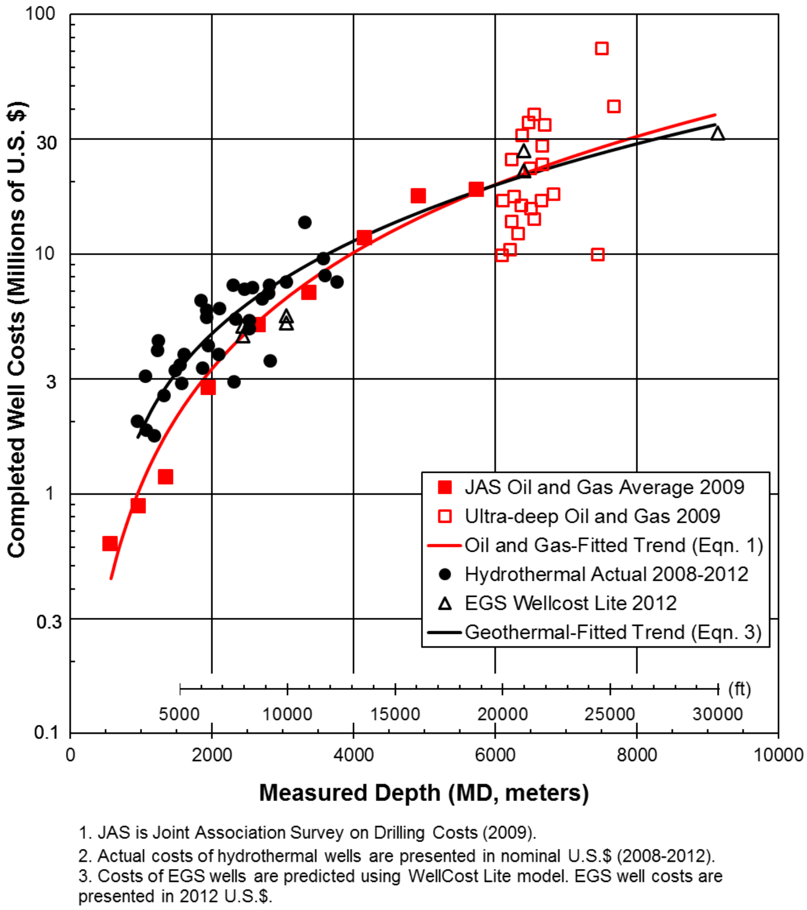


Figure 11. Comparison of well costs for on-shore oil and gas drilling with geothermal wells including actual hydrothermal well costs and EGS WellCost Lite predicted well costs.

5. POTENTIAL TRANSFORMATION ROLE OF LOWER TEMPERATURE GEOTHERMAL ENERGY IN THE NORTHEASTERN U.S.

For geothermal energy to have a national impact as a major energy supplier in the U.S., deployment must approach exajoule (EJ) levels and utilize low grade hydrothermal or EGS resources. In low grade hydrothermal or EGS regions, the costs of drilling as a function of depth will limit produced fluids to lower temperatures. This limitation favors applications for direct use and/or co-generation of electricity and heat. The Northeast region of the U.S. is of special interest because of moderate grade geothermal gradients and substantial annual heating loads during the long winter months.

In the sections that follow, two case studies are presented to illustrate possible options for deploying low grade geothermal energy systems in the Northeast: 1) deployment of district heating on the Cornell campus and 2) deployment of GDH in the rebuilding of aging infrastructure in mid-size cities and towns in NY and PA.

6. CASE STUDY 1 – DEPLOYMENT OF DISTRICT HEATING ON THE CORNELL CAMPUS

6.1 Context and Scope

A paper that was presented at the Geothermal Resources Council (GRC) annual meeting in Sacramento, CA in 2010 introduced the idea of a hybrid geothermal biomass system to provide both electricity and heat for Cornell's campus of 30,000 students, staff, and faculty. It was a collaborative effort involving earth scientists and engineers at Cornell University, David Blackwell's group at SMU and Brian Anderson's group at West Virginia University. A summary of the GRC paper follows below; for full documentation see Tester, Blackwell, Anderson and others (2010). A key objective of this study was to explore the potential for geothermal space heating and co-generation using Cornell's campus as a representative site for commercial-scale utilization of lower grade EGS resources in the eastern U.S. There were two motivating factors behind this choice: 1) Cornell's Ithaca campus has a large heating demand given its northern latitude in upstate New York State, and 2) Ithaca is located in a region that has moderate geothermal heat flow and gradient estimates.

Also, Cornell's Climate Action Plan (CAP) calls for the use of low carbon renewable resources along with the deployment of aggressive on-campus energy efficiency measures to substantially reduce and eventually eliminate carbon emissions. Before 2010, Cornell was consuming about 65,000 tons of coal per year prior to the development of its co-generation plant—a major upgrade to a natural gas fired system for heating and power generation on campus that is now operational and has lowered carbon emissions by about 25%. Achieving further reduction in emissions will require switching to renewable sources.

High electrical loads and high thermal energy demand for winter heating in the northern latitudes of the U.S would be heavily impacted by future gas and oil supply disruptions and could eventually lead to regional population shifts and declines in regional economic viability. With a limited availability of solar and wind resources in the Northeast, viable alternatives to coal are needed. Geothermal resources in the eastern U.S. are large in terms of their stored thermal energy but they are at greater depths to those available in the western U.S.

Cornell already uses cold water extracted from a deep section of nearby Cayuga Lake for cooling and air conditioning its buildings, laboratories and dormitories during the summer months. Adding geothermal energy would complement Cornell's lake-source cooling by providing hot water for winter heating for Cornell's campus using an advanced co-generation system in conjunction with other renewable resources such as biomass. Produced fluids from an engineered geothermal reservoir extracted at temperatures ranging from 80 to 120ºC would be connected to the campus's district heating network. During warmer periods geothermal heat could also be used for electric power generation. Figure 12 provides a schematic of the proposed plan.

Implementing Cornell's approach would result in a meso-scale, publicly-accessible demonstration of enhanced geothermal energy use suitable for replication by any large institution or industry. In its final stage, the EGS system would include multiple production and injection wells reaching up to about 4,300 m (14,000 ft) below ground surface into pre-Cambrian crystalline "basement" rock where temperatures could reach 150ºC. Heated geothermal fluids brought to the surface could supply energy to a combined heat and power co-generation facility utilizing organic Rankine-cycle engines, direct plate-and-frame heat exchangers, and heat pumps (as needed). Acquired thermal and electrical energy would be directly interconnected to Cornell's existing district energy system, which supplies 30MWe of electricity and 1.8 PJ (1.8 trillion Btu) per year of thermal energy for heating buildings within the Cornell community.

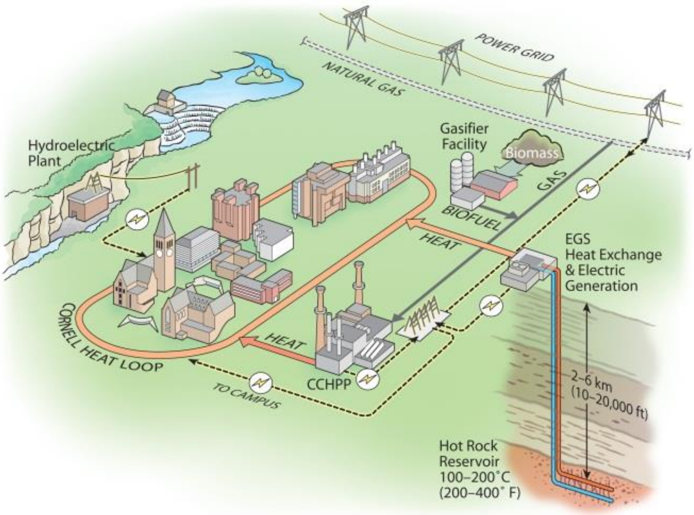


Figure 12. Schematic of Cornell's planned hybrid electric power and district heating co-generation system utilizing geothermal and biomass energy sources.

6.2 Assessment of the Geothermal Potential in the Ithaca, NY Region

In order to quantify the suitability of the Ithaca site for a low temperature geothermal demonstration, a comprehensive evaluation of regional and local geologic and geophysical data is underway. Key elements include the region's geology, the state of stress, heat flow and geothermal gradients, regional seismicity, and seismic risk. The composition and structure of the overlying sedimentary cover above basement rock is known as are regional stresses and are described in the next section. In terms of the geothermal heat resource itself, our immediate focus has been updating existing legacy heat flow and gradient information with new BHT data from recent extensive gas drilling activities. In addition, geologic information from the extensive outcrop of basement in the nearby Adirondack Mountains, and seismic reflection data from gas exploration surveys (2D and 3D) are being evaluated. New measurements of thermal properties of basement samples (e.g. from the Adirondacks) and *in situ* fluids (e.g. magnetotelluric) will be acquired as necessary. Background seismicity, a critical element for assessing of any future induced seismicity, will be calibrated by deployment of a dense surface seismograph network in the target area, to be operated for the two year duration of this proposed study.

New York State's geothermal resource differs from that found in the western states in terms of rock types, heat flow, and resulting temperature gradients. Heat flow measurements for the Adirondack Mountains have typical values of 38 mW/m^2, somewhat lower than the typical heat flow values for the adjacent Canadian Shield (45 mW/m^2). If the basement rocks in the Ithaca area are analogous to those exposed in the Adirondacks, they are likely to have similar heat producing capacity.

To evaluate the feasibility of EGS in the lower grade geothermal regions of Northeast, we designed a GDH network for Cornell University. A comprehensive description of this project is provided in Lukawski and coworkers (2013). The proposed design provides a pathway to lowering Cornell's carbon emissions by augmenting the existing combined-cycle natural gas system with both low-temperature geothermal energy and biomass. The configuration of this system is presented in Figure 13. The thermal output of the EGS reservoir is boosted by a torrified biomass boiler during peak heat demand periods. The required biomass feedstocks could be produced on Cornell's 14,000 acres of agricultural land. The heat generated by EGS and the biomass boiler is distributed to Cornell buildings through an improved pre-insulated hot water district heating network and is then cascaded to Cornell's greenhouses, where low-temperature heating systems can be implemented. By thermally cascading the heat streams, we can supply a range of end-use applications including agriculture, swimming pools, snow melting, and others. This is achieved by utilizing the heat output from one process as a heat input into another process. In addition to district heating, we also considered using an Organic Rankine Cycle (ORC) power plant to convert excess heat from EGS during summer periods into electricity.

A thermoeconomic model was created to evaluate the performance of this conceptual hybrid energy system over a range of ambient temperatures typical for the Northeastern U.S. The system was optimized with respect to district heating distribution temperature, flow rates, size of heat exchangers, and the sizes of geothermal and biomass heat sources. The goal of optimization was to minimize the levelized cost of electricity (LCOE) of the whole Cornell energy system with its natural gas, geothermal, and biomass components.

We found that high costs of drilling deep geothermal wells in moderate gradient areas characteristic of the Northeast U.S.A. result in an optimum system configuration corresponding to low reservoir temperature and low district heating temperature. The geothermal wells should be deeper to provide 125ºC wellhead temperature if an ORC power plant is implemented. The use of an ORC power plant outside winter season allows the EGS system to maintain economic feasibility even if it large enough to cover both baseload and peak heating demands. If the geothermal energy is used only for direct-use applications and not electricity generation, the peak heat demand should be covered with a biomass boiler.

Addition of the proposed EGS-biomass system was found to lower Cornell's carbon dioxide footprint by 15% and reduce its natural gas consumption by 21%, while increasing the LCOE by only 0.7-0.8 ¢/kWhe. Given that the current prices of natural gas are close to their historical low, the GDH system at Cornell may be even more competitive in the future. In addition, geothermal and biomass systems provide a buffer from the price volatility of natural gas and other fossil fuels.

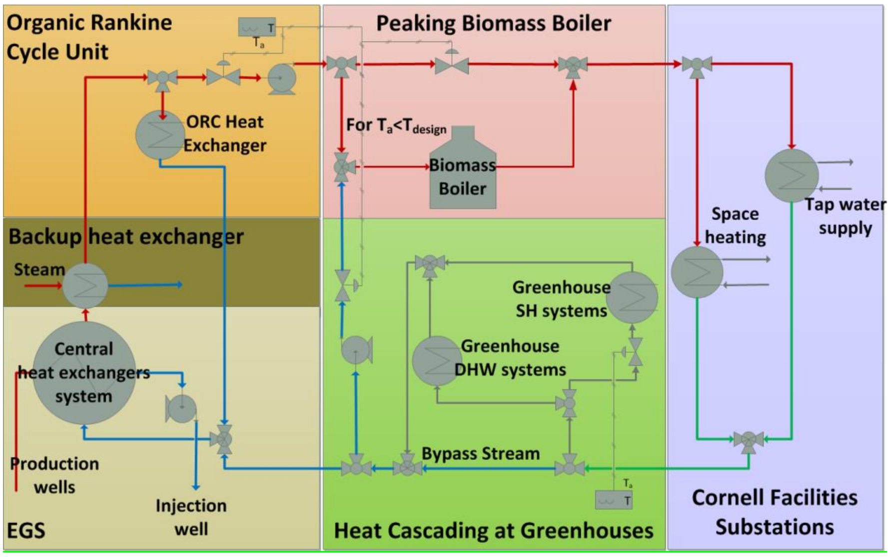


Figure 13. Conceptual hybrid geothermal – biomass energy systems for Cornell University. Red lines represent hot supply water and blue lines cold return water (Lukawski et al., 2012).

Cornell's existing infrastructure and high heating and electric loads provide a good match for a co-generation application of geothermal. Averaged over the last few years, Cornell's demand for electric power is about 30 MWe with about 65,000 tons of coal (1.8 trillion Btu) consumed per year for heating its buildings.

Based on anticipated performance metrics for existing geothermal resource developments, we conducted a preliminary parametric analysis of the levelized energy costs for both electricity and heat for a range of resource grades, reservoir performance, and financial factors expected for the proposed Cornell application. These are summarized below in Table 1.

The GEOPHIRES program has been applied to the Cornell campus using the parameters and assumptions shown in Tables 1 and 2. Two different geothermal gradients were considered (20ºC/km and 30ºC/km) and three different production temperatures (110ºC, 130ºC and 150ºC). In each case, the well configuration is a doublet and the flow rate is 50 kg/s. The capacity factor is taken at only 70%, not as high as it would have been for electricity production, because limited heating is required during the summer months. Also, the discount rate is only 3%, assuming cheap public financing is available for these type of projects. Further, the geothermal reservoir is considered of large enough spatial dimensions without short-circuiting resulting in a small drawdown rate of only 0.5%/year. Table 2 shows that the levelized cost of heating (LCOH) for a GDH system for the Cornell University campus ranges from 8 to 13 $/MMBTU, with lower values for higher geothermal gradients and higher production temperatures. These values compare favorably with current costs in the U.S. for residential natural gas boilers, ranging between 12 and 16 $/MMBTU (Beckers et al., 2014).

Table 1. Parameters used in all EGS scenarios for the Cornell Campus in Ithaca, NY.

Parameter	Value
Producer Flow Rate	50 kg/s per well
Reservoir Model	Percentage Thermal Drawdown
Well configuration	Doublet
Surface Plant capital costs	$150/kW_{th}$
Hydraulic Impedance per Well-Pair	0.15 MPa·s/L
Production Wellbore Temperature Drop	Ramey's Model
Water Loss Rate	2%
Geofluid Pump Efficiency	80%
Well Casing Inner Diameter	0.2 m
Discount Rate	3%
Plant Lifetime	30 years
Reservoir Temperature Drawdown Rate	0.5%/year
Capacity Factor	70%
Fluid Temperature Drawdown Threshold Before Rework	14%
Electricity Rate for Pump Power in Direct-Use Mode	7 ¢/kWh_e
Ambient Temperature	15ºC

Table 2. Resource cases and results for EGS scenarios for the Cornell campus in Ithaca, NY.

Resource Case	Low-Grade			Medium-Grade		
Geothermal Gradient	20ºC/km			30ºC/km		
Initial Production Temperature	~110ºC	~130ºC	~150ºC	~110ºC	~130ºC	~150ºC
Well Depth (km)	5.0	6.0	7.0	3.3	4.0	4.7
LCOH (2012 $/MMBTU)	13.3	12.8	12.3	9.2	8.8	8.5
Power Output (MW_{th})	11.1	14.7	18.2	10.8	14.7	18.5

7. CASE STUDY 2 – DEPLOYMENT OF GEOTHERMAL DISTRICT HEATING IN THE REBUILDING OF AGING INFRASTRUCTURE IN MID-SIZED CITIES AND TOWNS IN NY AND PA

7.1 Overview and Scope

EGS could supply a significant fraction of the low-temperature (<125ºC) thermal energy used in the U.S. through GDH. In this study we develop a regional model to evaluate the potential for EGS district heating in the states of New York and Pennsylvania by simulating an EGS district heating network at each population center within the study region and estimating the LCOH from GDH for each community. The district heating potential using EGS was evaluated for 2,894 towns in NY and PA. LCOHs were then compiled for each town and combined to produce into a supply curve for the region.

7.2 Specific Objectives and Approach

The objective of this work is to evaluate opportunities for the use of low-temperature geothermal resources in district-heating applications in NY and PA, and to develop a supply curve for those applications. By exploring options for these two states we hope to provide a representative sample of what could be possible for many other states located in the northern tier of the U.S. where heating demands are high.

The U.S. Department of Energy and other organizations have been using supply curve analysis to evaluate renewable energy technologies for decades. Recently, the National Renewable Energy Lab (NREL) published a supply curve for geothermal electricity production in the United States (Augustine et al. 2010; Augustine 2011). However, that study evaluated geothermal electricity production exclusively while neglecting geothermal direct-use and district heating possibilities. This leaves an opportunity for development of a supply curve for district heating applications, of which there have been very few, if any, attempts to do.

Supply curves are generally used to visualize the cost of supplying a given quantity of a certain good (in this case heat). For energy resources the price of supplying the good (i.e. energy) typically increases as more total energy is required. This is because the highest quality and most affordable resources will generally be developed first, followed by successively poorer-grade and more expensive resources. The supply curve developed in this study will plot the total cumulative heating capacity in the study region against the projected levelized cost of supplying that heat.

District heating applications are highly location-dependent. While in geothermal electricity production the assumption can be made that a resource may be developed anywhere and the power produced can simply be sold to the national power grid, in GDH applications the hot water produced can typically only be transported a few kilometers from its source for economic reasons. Using heavily-insulated piping and high flow rates can increase the distance hot geofluid may be transported (up to 68 km in one Icelandic case), but these measures also significantly increase the capital cost of the piping and pumping costs, respectively. Additionally, there are inherent limitations in storing thermal energy in large quantities or for long periods of time to meet daily or seasonal demand fluctuations. Therefore in EGS applications the heat must remain in the subsurface reservoir (which doubles as a storage medium) until it is needed. As a result, GDH systems can only be effectively developed where the geothermal resource also coincides spatially with an area that has a high heating demand that would, from an economic perspective, ideally be constant throughout the year.

Hence the first goal of this study is to identify specific locations across NY and PA where high geothermal gradients coincide with towns with a high heating demand and demand density. This will be achieved using an iterative approach to model a conceptual specified GDH system in each community in the target region. Estimated LCOH will be used to plot the supply curve for the region, compare GDH systems across communities, and highlight the most promising communities for initial and future GDH development.

The second goal is to identify the potential opportunity for reducing the cost of GDH systems. This was achieved using a sensitivity analysis on the input variables of the economic model to see how they affect estimated LCOH relative to specified base case conditions. Important variables include geothermal gradient, reservoir flow productivity, capital cost for infrastructure, drilling costs, and financial metrics. Details on the sensitivity analysis are not presented here; see Reber et al. (2014) for more information. The overall modeling approach used for the study showing submodels and their interconnections is shown in Figure 14.

7.3 Findings

Our evaluation revealed that EGS district heating has the potential to supply cost-effective energy for space and water heating in several NY and PA communities in the near future (see Figure 15). To realize wider deployment, modest improvements in EGS technology, escalation of natural gas prices, and/or government incentives will likely be required to enable GDH to compete with other heating alternatives today. EGS reservoir flow rates, drilling costs, system lifetimes, and fluid return temperatures have significant effects on the LCOH of GDH and thus will provide the highest return on R&D investment, while creative implementation strategies can help EGS district heating overcome initial cost barriers the exist today.

To summarize, geothermal district heating has cost-saving potential in NY and PA. Given that these states are representative of Northern Tier locations in the US, the geothermal potential for district heating is very large with successful EGS technology.

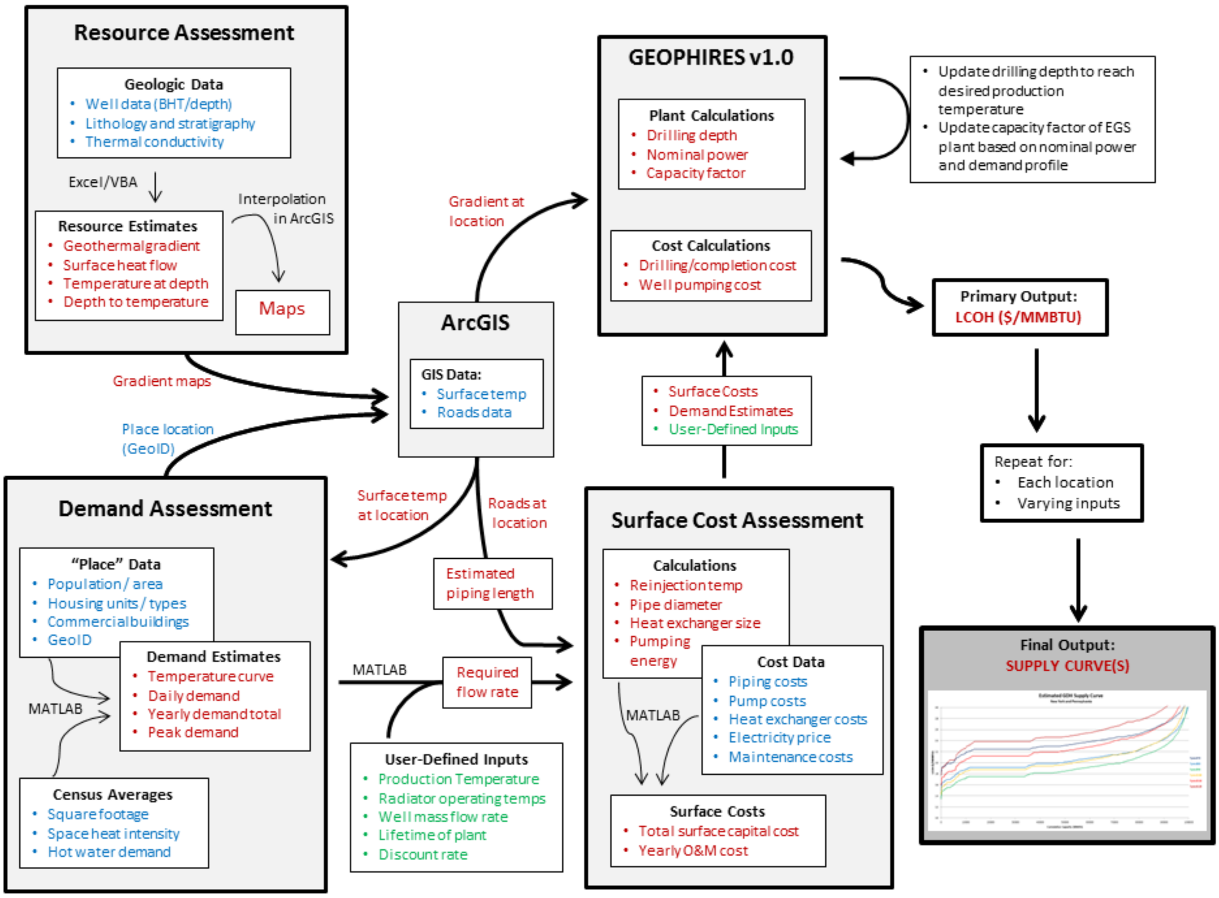


Figure 14. Overall work-flow diagram for the model and data processing structure developed to evaluate geothermal district heating options. (Adapted from Reber et al., 2014).

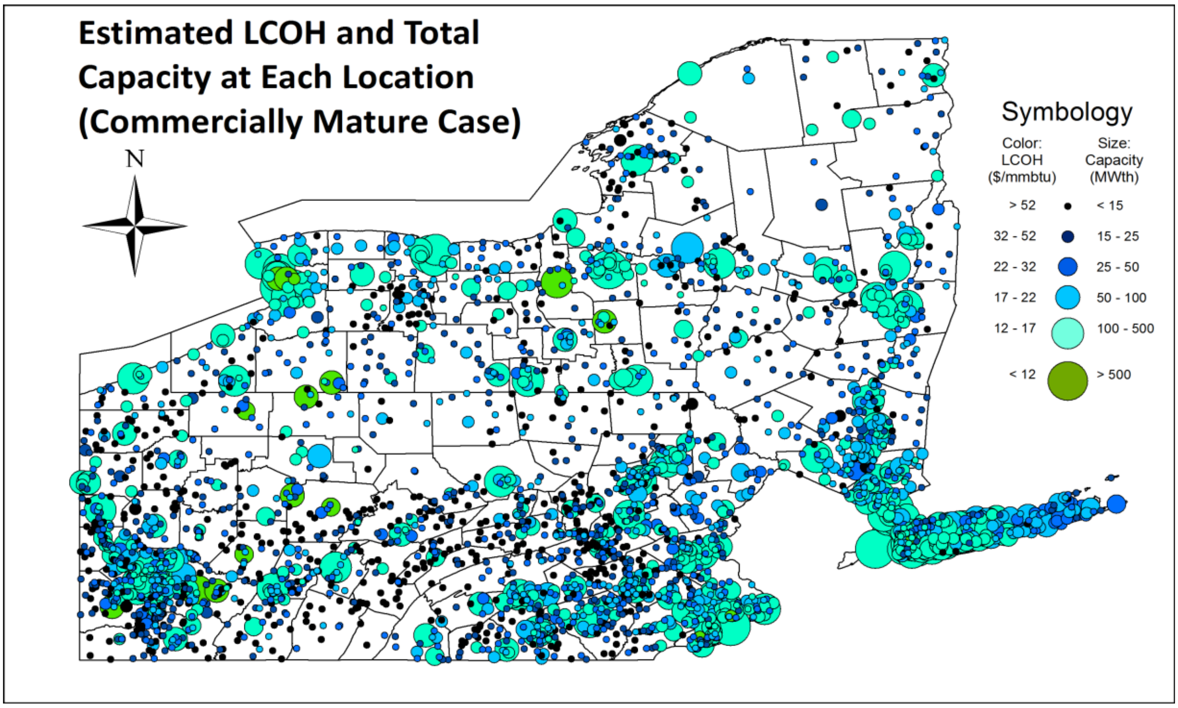


Figure 15. Estimated LCOH and total heating capacity for every community in the dataset given commercially mature phase assumptions (see Reber et al. (2014) for details).

8. CONCLUDING REMARKS AND RECOMMENDED PATH FORWARD FOR THE U.S.

Given that the geothermal resource grade is uniformly lower in the eastern U.S. than in the western states, deeper, more costly wells are needed to reach comparable useful rock temperatures. Inevitably, this leads to having to utilize lower rock temperatures to achieve acceptable economic performance with lower gradients and the high costs of drilling deep. To maximize the utilization of the extracted heat, it makes sense to use co-generation of heat and electricity to offset the thermodynamic losses incurred by just generating electricity. Ongoing advances in drilling and reservoir stimulation and completion technologies coupled to rising energy prices for electricity, heating oil and natural gas suggest that lower grade geothermal resources are now within reach.

The rationale behind the selection of Cornell University in Ithaca, NY as a demonstration site for low temperature geothermal energy utilization is based both on the favorable geologic conditions present in the region and the existence of a fully operational co-generation system for the campus. Cornell's energy use level is representative of many rural communities and cities with populations ranging from 10,000 to 50,000 in the eastern region of the U.S. at latitudes where a significant heating demand exists.

Cornell's existing assets, including a new gas-fired, cogeneration power plant, lake source cooling and operational district heating infrastructure, greatly reduce the capital investment needed to demonstrate low temperature geothermal utilization at scale. Furthermore, with access to substantial amounts of biomass feedstocks from its agricultural residuals, low-intensity energy grasses, and forest products on Cornell land, an opportunity exists to use gasified biomass to supply Cornell's combined cycle heating and power plant. Lastly, in the long term significant financial advantages could result from the University's commitment to deploy a lower carbon energy supply system using local renewable resources. This leads to lower discount rates for capital investments and should be representative of future public investments in municipal geothermal energy supply systems.

The second case study that examined the potential for geothermal district heating in the NY and PA region of the Northeast reinforced the findings obtained for the Cornell campus study. With successful EGS technology in place to provide sufficient reservoir productivity, lower grade geothermal resources with average gradients ranging from 25 to 40 ºC/km provide a scalable option for transforming American infrastructure for heating buildings from a discretely supplied oil, gas and propane system to a distributed district heating system. Estimated capital investments for drilling wells and installing required surface infrastructure in much of the Northern Tier of the U.S. where heating demand is the greatest yield levelized costs for supplying heat competitive with current delivered natural gas prices.

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