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Numerical Reservoir Simulation of the Salton Sea Geothermal Resource for Power Generation

BHE Renewables, LLC

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0	1 May 2023	Power Generation Report	MP	JWL	AR-T
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2	4 May 2023	Typographical corrections	MP	JWL	AR-T

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EXECUTIVE SUMMARY

Introduction

BHE Renewables, LLC ("BHER") requested GeothermEx to provide long-term forecasting by numerical simulation of potential power generation capacities that can be supported by the Salton Sea Geothermal Field ("SSGF"). GeothermEx conducted a study that assessed resource adequacy in connection with the proposed BHER development projects at the SSGF: the Black Rock Geothermal Project (77 megawatts (MW) net), the Elmore North Geothermal Project (140 MW net), and the Morton Bay Geothermal Project (140 MW net). The goal of this resource adequacy study was to determine if the reservoir could support the power generation requirements of the proposed BHER development projects as well as existing facilities operated by BHER and others.

Field Description

The SSGF is located on the southeastern shore of the Salton Sea, about 170 miles southeast of Los Angeles. The BHER portion of the field is divided into four operating geothermal power facilities: Region 1 (comprising Units 1 to 5), Region 2 (comprising the Vulcan, Hoch and Turbo-expander plants), Elmore, and Leathers. The existing BHER facilities are comprised of 10 power plants with a combined generating capacity of approximately 345 MW net. The study also took into account other facilities in the SSGF that are currently in operation or under development. The only other currently operating facility is the John Featherstone plant at Hudson Ranch, operated by Hudson Ranch Power I (HRPI, a subsidiary of Cyrq Energy) on the eastern side of the field, with a generating capacity of 49.9 MW net. Controlled Thermal Resources (CTR), whose leasehold is located in the north and northeast portions of the field, is currently developing a new plant (CTR-1 at Hell's Kitchen), with a generating capacity of 49.9 MW net.

Modeling Approach

For the purposes of the GeothermEx study, CTR-1 was projected to come online in September 2023, and the three proposed geothermal projects of BHER were projected to come online in December 2026.

The steps in numerical simulation for this study included:

- Creating a model with sufficient lateral extent to cover the entire geothermal resource;
- Calibrating the initial-state model by matching pre-oprerations reservoir data;
- Calibrating the history-matching model by matching historical production data; and
- Forecasting power production characteristics of existing and proposed facilities.

The new numerical reservoir model of the Salton Sea geothermal resource is based on a model previously developed by GeothermEx in 2009, updated with measured reservoir and production information since that time. As part of this study the model was extended laterally in all directions to allow for full coverage of the currently developed area and additional areas that are believed to have development potential.

In the initial-state phase of the model calibration, the objective is to obtain a reasonable match to pre-operations thermodynamic conditions in the reservoir. It is normal for measured data in certain wells not to be matched exactly, because a number of the wells have been drilled after power plants have come online, and initial measurements in these wells are affected by changes in reservoir temperatures and pressures that have already occurred. However, calibration of the current simulation model to initial-state conditions has been excellent, with measured and simulated temperatures differing by less than 20°F in the main production areas. With this result, the model is considered to be well calibrated against the initial state of the field, and it has been suitable for use in matching the reservoir's response to operations (the history-matching phase of calibration).

For the history-matching phase, GeothermEx was provided with confidential data collected through more than three decades of operations on reservoir pressure trends measured in observation wells, production enthalpy, total dissolved solids (TDS), and non-condensable gas (NCG). These data sets were used as calibration parameters for the model. The results of the history-matching phase have shown that the model was successful in simulating the behavior of the reservoir under the historical conditions of production and injection. Pressure, enthalpy, TDS, and NCG trends measured from the production wells have been closely replicated by the numerical model. Thus, the model is considered well calibrated for use in forecasting reservoir behavior under various production and injection scenarios.

Conclusion

The results from this study indicate that the geothermal reservoir of the SSGF is quite robust. The simulated forecast demonstrates that the resource can accommodate both existing geothermal power plants and the proposed geothermal power plants (Black Rock, Elmore North, and Morton Bay) over the horizon of the evaluation (through 2065).

1. INTRODUCTION

1.1 Purpose and Scope

BHER has requested GeothermEx to provide long-term forecasting of generation from BHER's Salton Sea geothermal projects using numerical simulation. The Salton Sea geothermal field is located on the southeastern shore of the Salton Sea, about 170 miles southeast of Los Angeles. The BHER portion of the field is divided into four facilities: Region 1 (comprising Units 1 to 5), Region 2 (comprising the Vulcan, Hoch and Turbo-expander plants), Elmore, and Leathers. The existing BHER facilities comprise 10 power plants with a combined capacity of approximately 345 MW net. One additional existing facility (the John Featherstone plant at Hudson Ranch) is operated by Hudson Ranch Power I (HRPI, a subsidiary of Cyrq Energy) on the eastern side of the field, with a capacity of 49.9 MW net.

BHER is planning three new development projects at the Salton Sea: Black Rock (77 MW net), Elmore North (140 MW net), and Morton Bay (140 MW net). In addition, CTR is currently developing a new plant (CTR-1 at Hell's Kitchen), with a capacity of 49.9 MW net. Figure 1.1 shows the locations of existing projects and the general production and injection areas for the planned developments in the Salton Sea, as well as the numerical simulation grid used in the current study.

This study has been structured to focus primarily on resource adequacy for the BHER development projects and potential impacts on BHER's existing facilities. Other projects (Hudson Ranch and CTR-1) have been included in this study to further examine the potential impacts of existing and imminent projects in offsetting areas. Reservoir parameters including reservoir pressure, reservoir enthalpy, TDS and NCG have been predicted using a numerical reservoir model over a 40-year horizon (2026-2065). The forecasting of these reservoir parameters has been used to confirm the adequacy of the resource to support full power generation for the existing and development projects.

For the purposes of the current study, the combined schedule of development projects by BHER and CTR is projected as follows:

a. CTR-1 (Hell's Kitchen): 49.9 MW net, operational on 1 September 2023
b. Black Rock: 77 MW net, operational on 31 December 2026
c. Elmore North: 140 MW net, operational on 31 December 2026
d. Morton Bay: 140 MW net, operational on 31 December 2026

The scope of work for this project is summarized below:

Task 1: Create a model with sufficient lateral extent to cover the entire geothermal resource

GeothermEx has evaluated the currently accepted conceptual model of the Salton Sea field, enabling the creation of a simulation grid that spans 48,200 feet in the E-W direction and 56,000 feet in the N-S direction (Figure 1.2). The model has a total vertical thickness of 11,000 feet, extending from an elevation of approximately -1,000 feet relative to mean sea level ("msl") down to -12,000 feet msl. The dimensions of the model cover the currently developed area and additional areas that are believed to have development potential. The numerical model is based on a model previously developed by GeothermEx in 2009. Additional acreage has been added as appropriate to the four sides of the previous model, to minimize potential boundary effects.

Task 2: Model calibration

The expanded model was first calibrated against pre-operations data (initial-state matching), followed by calibration against historical data since the start of field operation (history matching). The data considered in the history-matching process were long-term trends in production enthalpy, temperature, and reservoir pressure. Well production and injection data were used as input to the numerical model, which was run for the duration of the field's operating history. Enthalpy and pressure trends calculated by the model were compared with measured enthalpy and pressure trends. Petrophysical parameters within the model (such as porosity and permeability) and the model's boundary conditions were adjusted as needed until the measured and modeled data sets converged.

Trends in non-condensable gases (NCG) were taken into account due to the effect of NCG on power generation. The inclusion of the NCG component in the model was technically straight-forward; however, because of the heavy computational requirement to incorporate NCG, the model took significantly longer to run. Nevertheless, GeothermEx included NCG in the model and successfully reproduced the NCG trends of individual wells, providing an additional calibrating parameter for the history-matching phase.

Task 3: Forecasting

After completing the model-calibration process , the model was used to make forecasts of reservoir performance. This included prediction of reservoir pressure, enthalpy, TDS and NCG through 2065. The forecast of these reservoir parameters has confirmed the adequacy of the geothermal resource to support power generation for the existing and development projects.

1.2 Data Sources

Field data from BHER were utilized in the development of the numerical model. Because the model has encompassed areas beyond those held by BHER, critical data from other areas were sourced in the public domain. In areas where little or no public data were available, GeothermEx made reasonable assumptions in consultation with BHER.

2. RESERVOIR MODEL CALIBRATION

As the first step in reservoir model calibration, the overall fluid and heat flow patterns of the Salton Sea geothermal system in its initial state were accurately matched with the model (Figure 2.1). Following this initial-state model calibration, detailed information about reservoir conditions at and near the wells, was ascertained by matching the historical performance data obtained from the field since initial operations. This process is called history matching.

For the history-matching phase, GeothermEx was provided with confidential data collected through more than three decades of operations on reservoir pressure trends measured in observation wells, production enthalpy, TDS, and NCG. These data sets were used as calibration parameters for the model. Figure 2.2 shows representative results of reservoir pressure history matching (measured and simulated reservoir pressure). Figure 2.3 shows representative results of history matching results for enthalpy, TDS and NCG. The history-matching results have shown that the numerical model was successful in simulating the behavior of the reservoir under the historical conditions of production and injection. Pressure, enthalpy, TDS, and NCG trends measured from the production wells have been closely replicated by the model. Thus, the model is considered well calibrated for use in forecasting reservoir behavior.

3. FORECASTING

The purpose of this numerical modeling has been to forecast key reservoir parameters for power generation (including pressure, enthalpy, TDS and NCG) through 2065. The modeling has allowed forecasting of power generation from the following existing and development projects:

Existing projects:

- Region 1 (comprising Units 1 to 5): 164 MW net.
- Region 2 (comprising the Vulcan, Hoch and Turbo-expander plants): 90 MW net.
- Elmore: 49 MW net.
- Leathers: 42 MW net.
- Hudson Ranch Power I: 49.9 MW net.

Development projects:

- Black Rock: 77 MW net
- Elmore North: 140 MW net
- Morton Bay: 140 MW net
- CTR-1 (Hell's Kitchen): 49.9 MW net

Table 3.1 summarizes the mass rates of production and injection assumed for each of these projects. The forecasting results were utilized to assess power generation over a 40-year horizon (2026-2065) and to confirm the adequacy of the geothermal resource to support power generation from the existing and development projects.

Figure 3.1 shows a representative forecast of reservoir pressure, and Figures 3.2 through 3.4 show forecasts of enthalpy, TDS and NCG for BHER's three development projects. The forecast results show modest declines in reservoir pressure and enthalpy through 2065, which indicates that the geothermal reservoir of the SSGF is quite robust. This modest decline in reservoir pressure and enthalpy could be mitigated by drilling additional make-up production and injection wells during the life of the projects in order to maintain sufficient production and injection capacity for full power generation. In conclusion, the resource adequacy study has demonstrated that the geothermal resource can accommodate both existing geothermal power plants and the proposed geothermal power plants (Black Rock, Elmore North, and Morton Bay) over the horizon of the evaluation (through 2065).

Tables

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Table 3.1: Assumed Production and Injection Rates in Salton Sea Forecasting

Facility	Net MW Capacity	Annual Average Production [a] (KPH)	Annual Average Hot-Brine Injection [a] (KPH)	Annual Average Condensate Injection (KPH)
Region 1	164	15,903	11,855	421
Region 2	90	8,590	6,446	579
Elmore	49	4,394	3,903	135
Leathers	42	3,995	3,385	123
Black Rock	77	6,190	4,677	385
Elmore North	140	10,294	9,296	657
Morton Bay	140	10,676	9,296	670
Hudson Ranch	49.9	4,660	4,287	93
CTR-1 (Hell's Kitchen) [b]	49.9	5,969	5,198	0

Notes

[a] Production and hot-brine injection are initial values. These change over time in the forecast as properties of produced brine evolve.

[b] CTR-1 was assumed to have a higher production requirement per MW and zero condensate injection due to mineral recovery processing.

Figures

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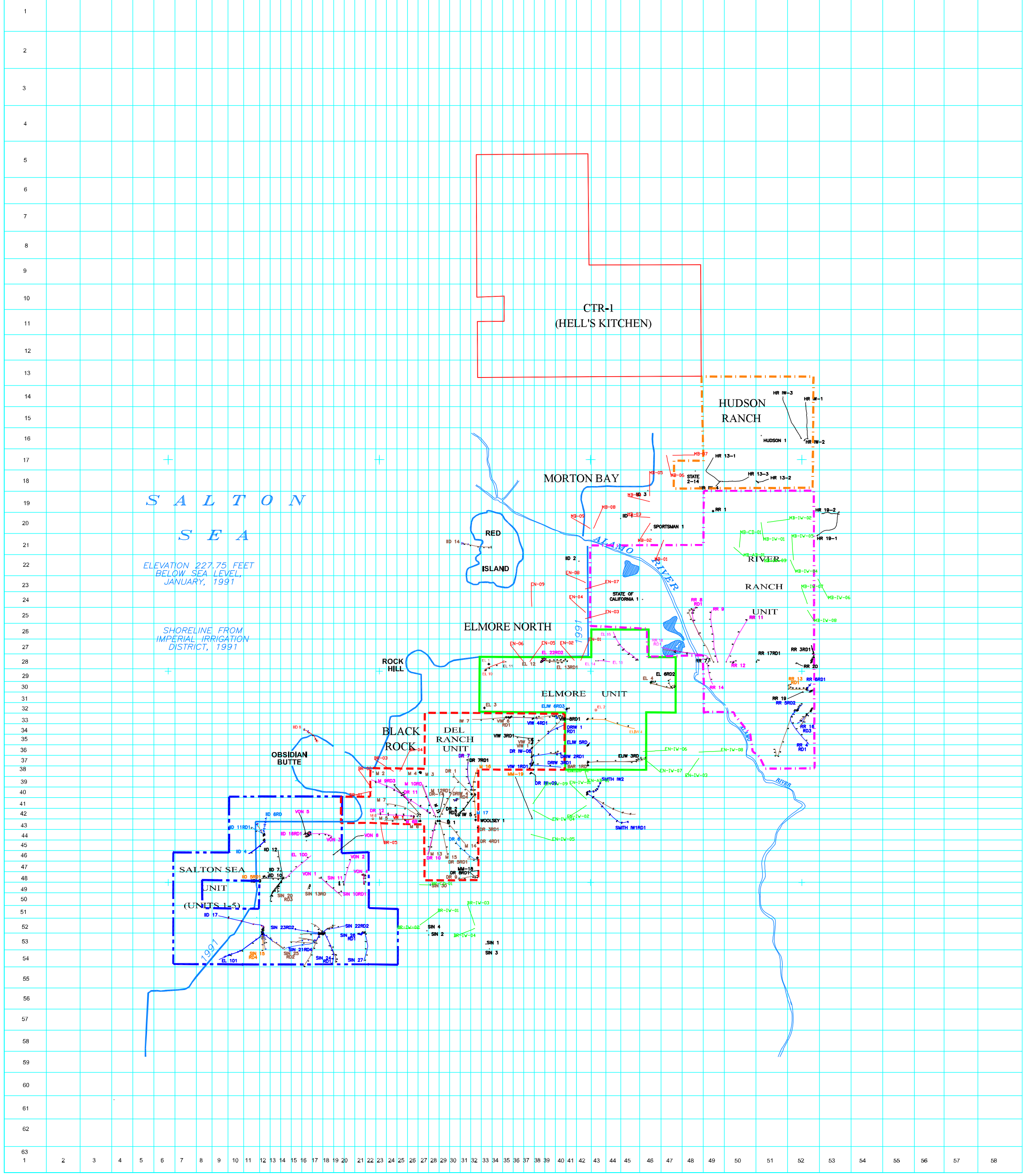

Figure 1.1: Well and Facility Locations, Salton Sea

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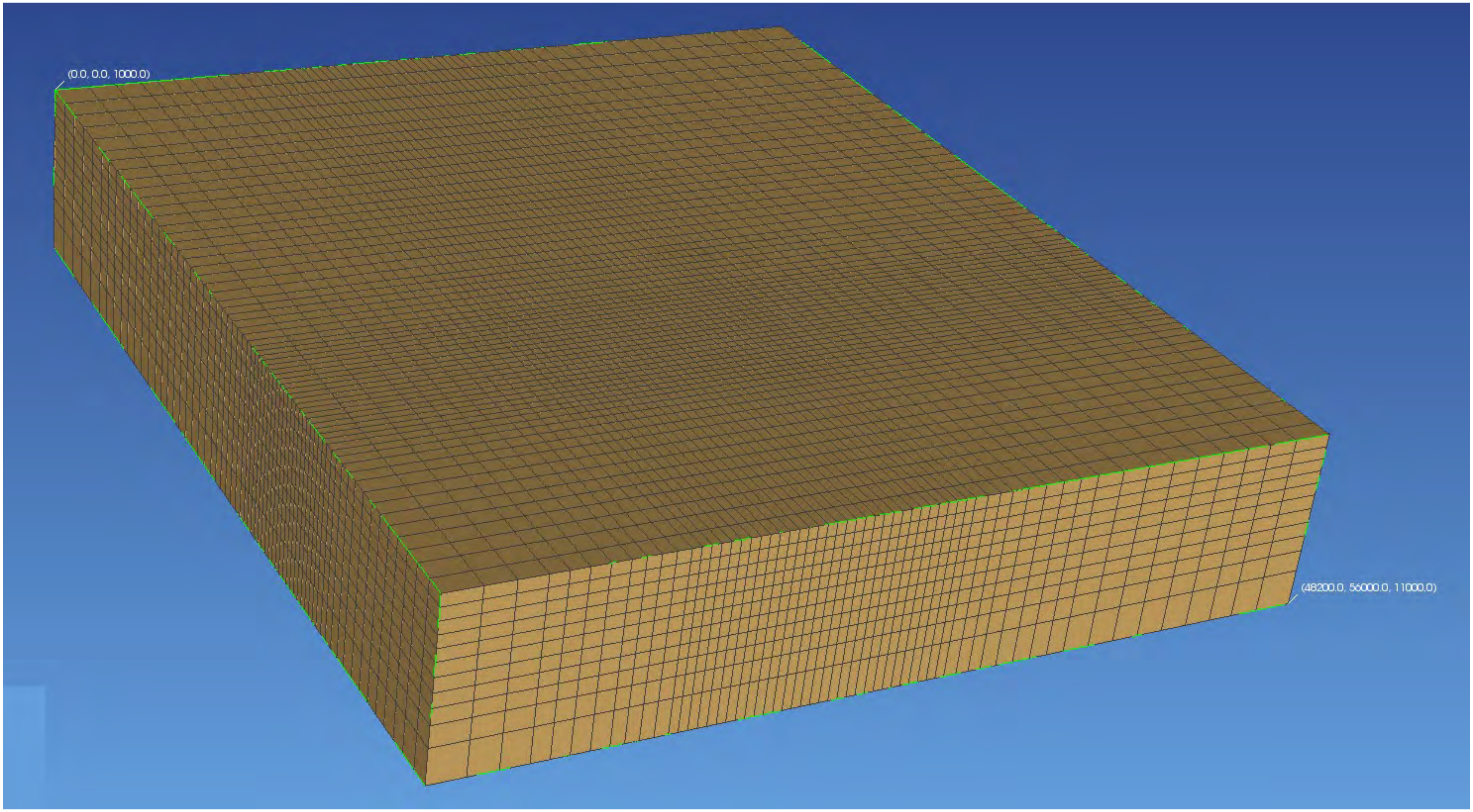

Figure 1.2 3-D View of the Salton Sea Numerical Model

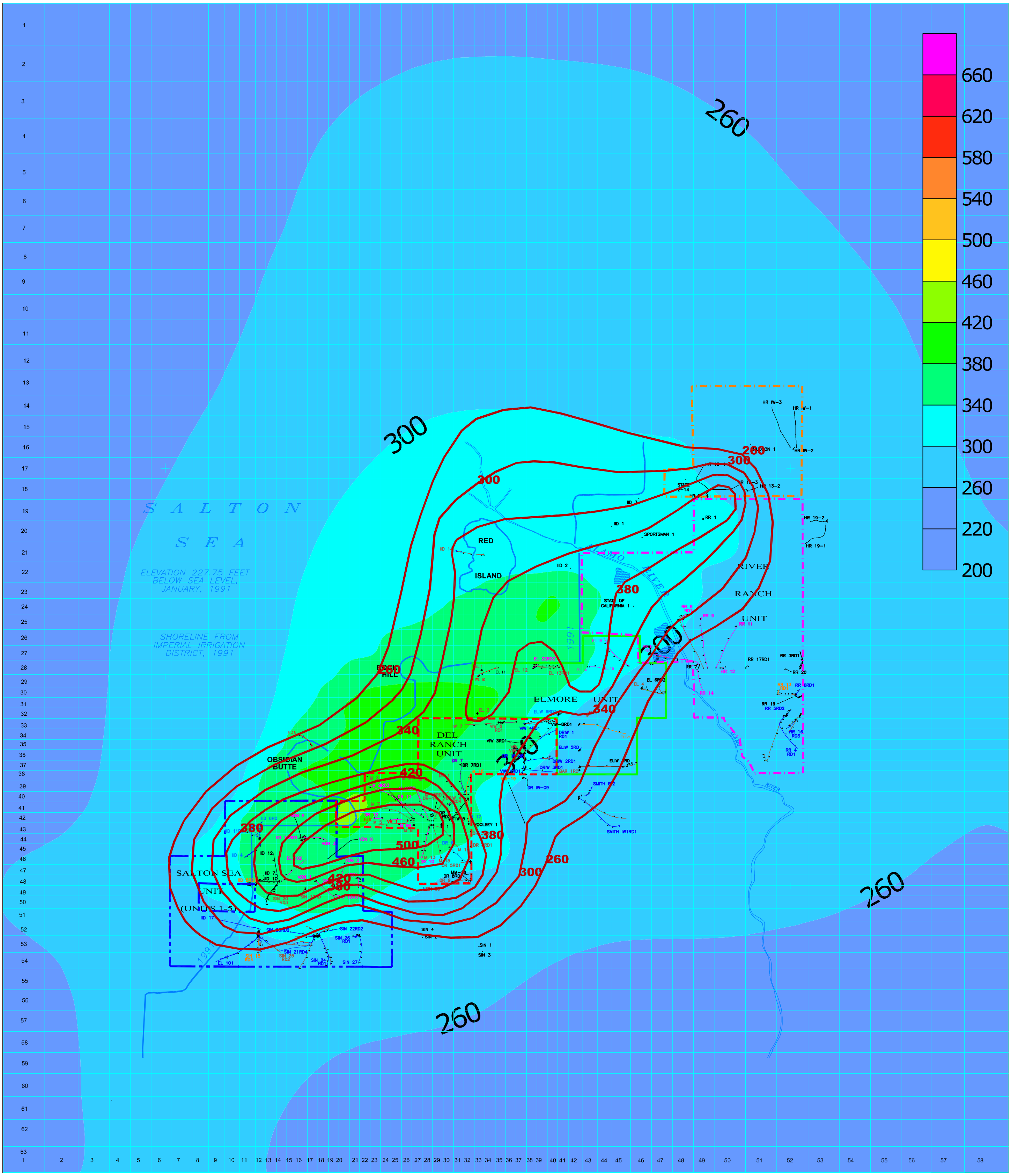

Figure 2.1 Matching of Subsurface Temperature at - 1,350 ft msl

GeothermEx

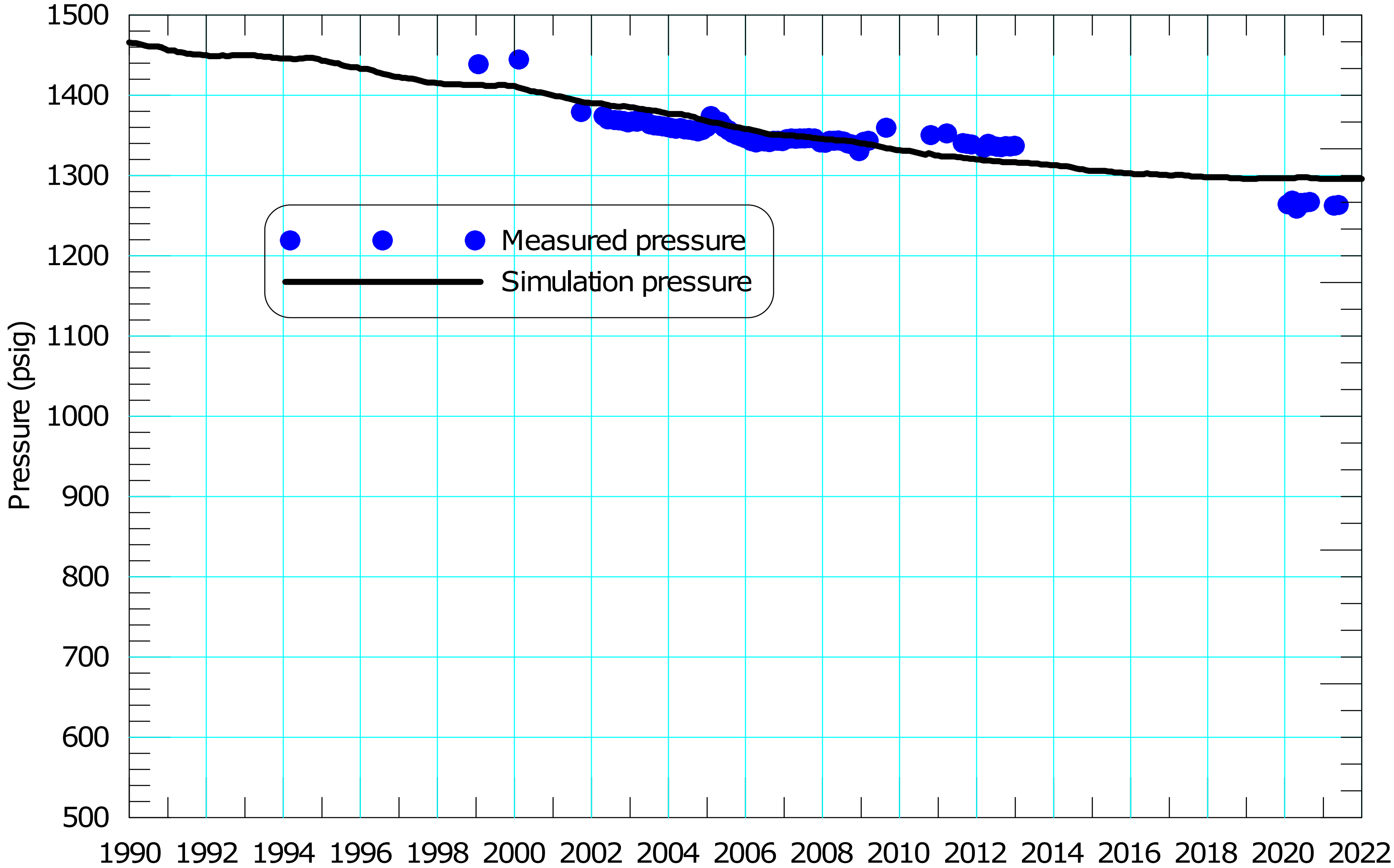

Figure 2.2 History Matching of Reservoir Pressure Data

GeothermEx

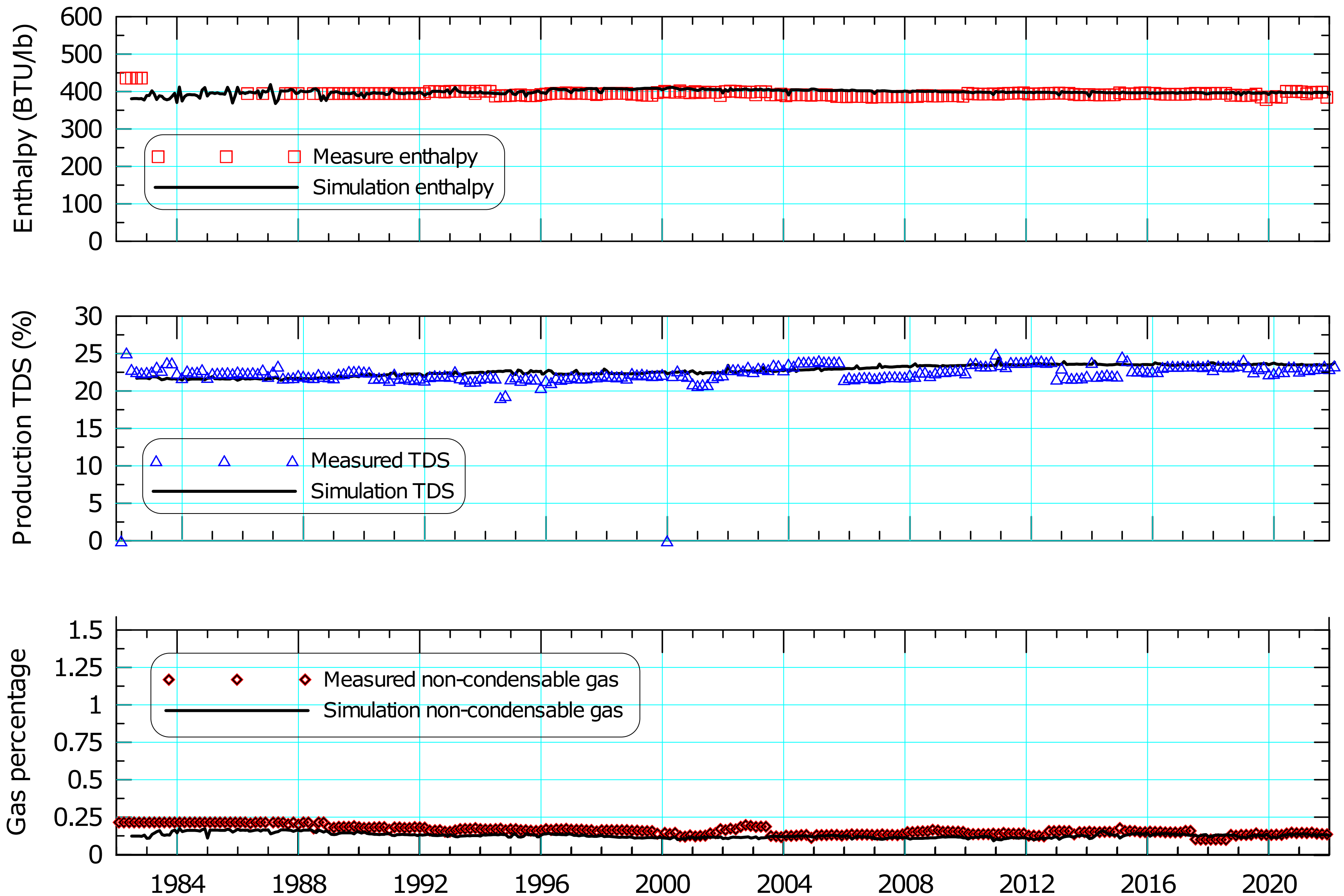

Figure 2.3 History Matching of Enthalpy, TDS and NCG

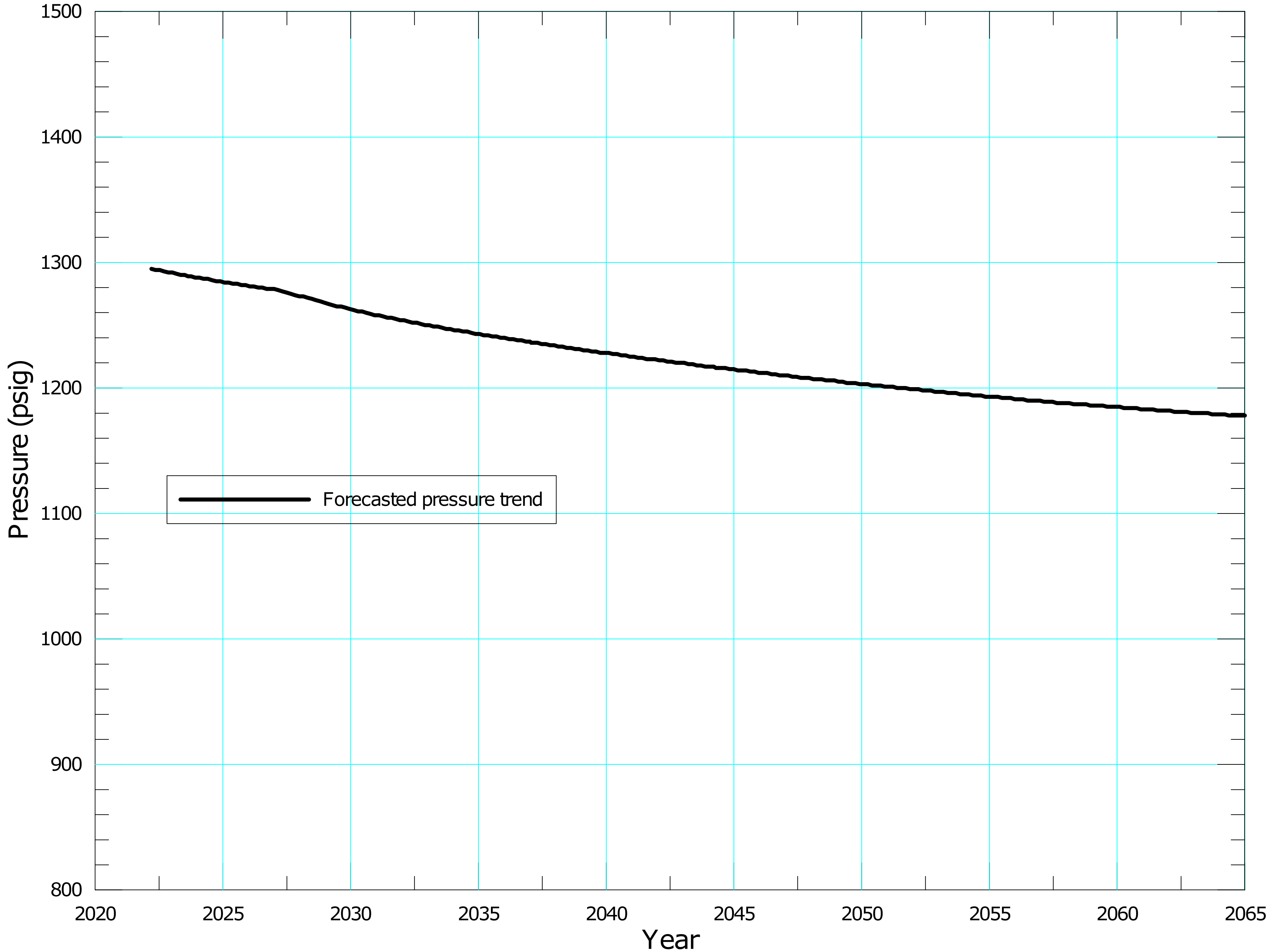

Figure 3.1 Forecast of Reservoir Pressure

GeothermEx

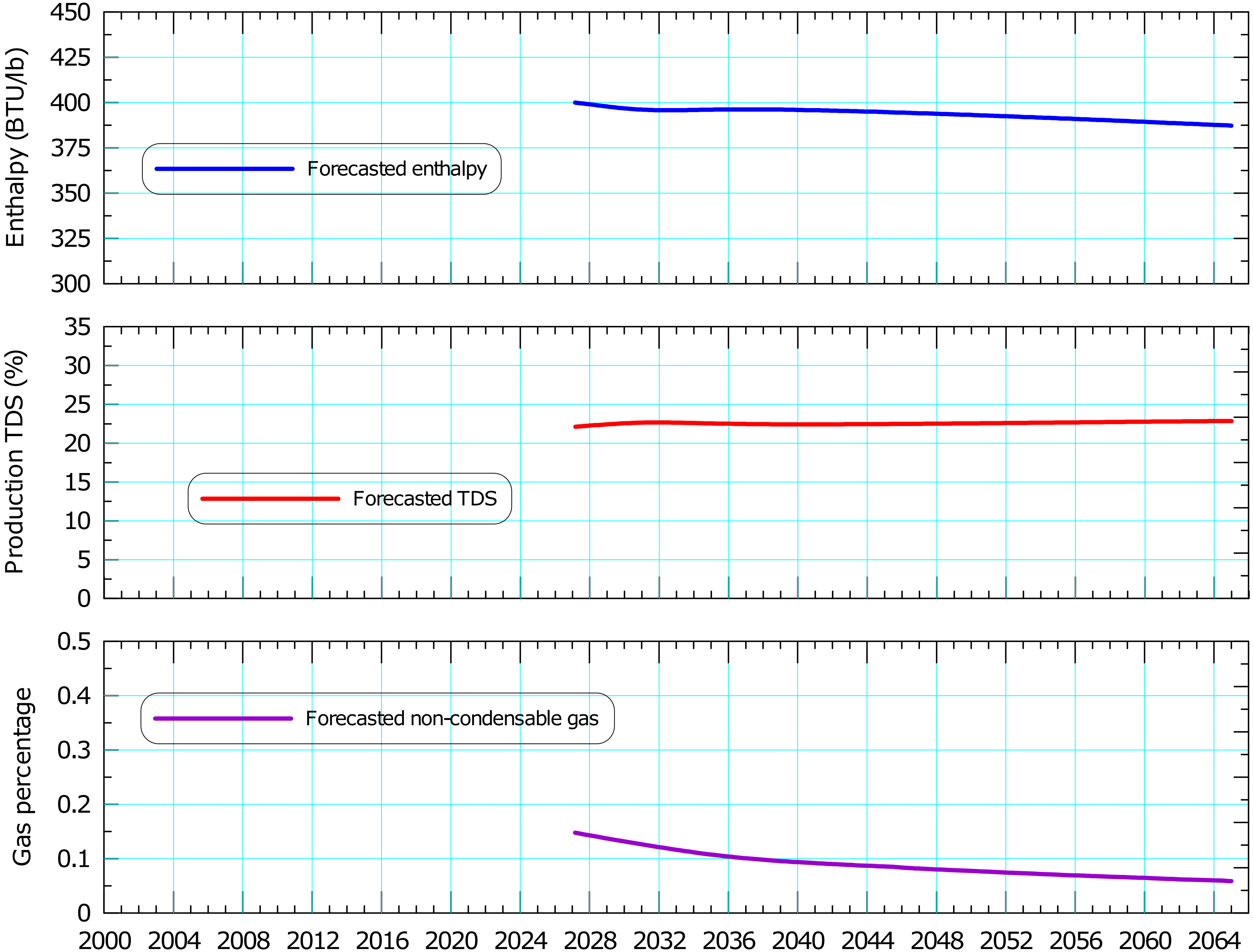

Figure 3.2 Forecast of Enthalpy, TDS, and NCG For Black Rock

GeothermEx

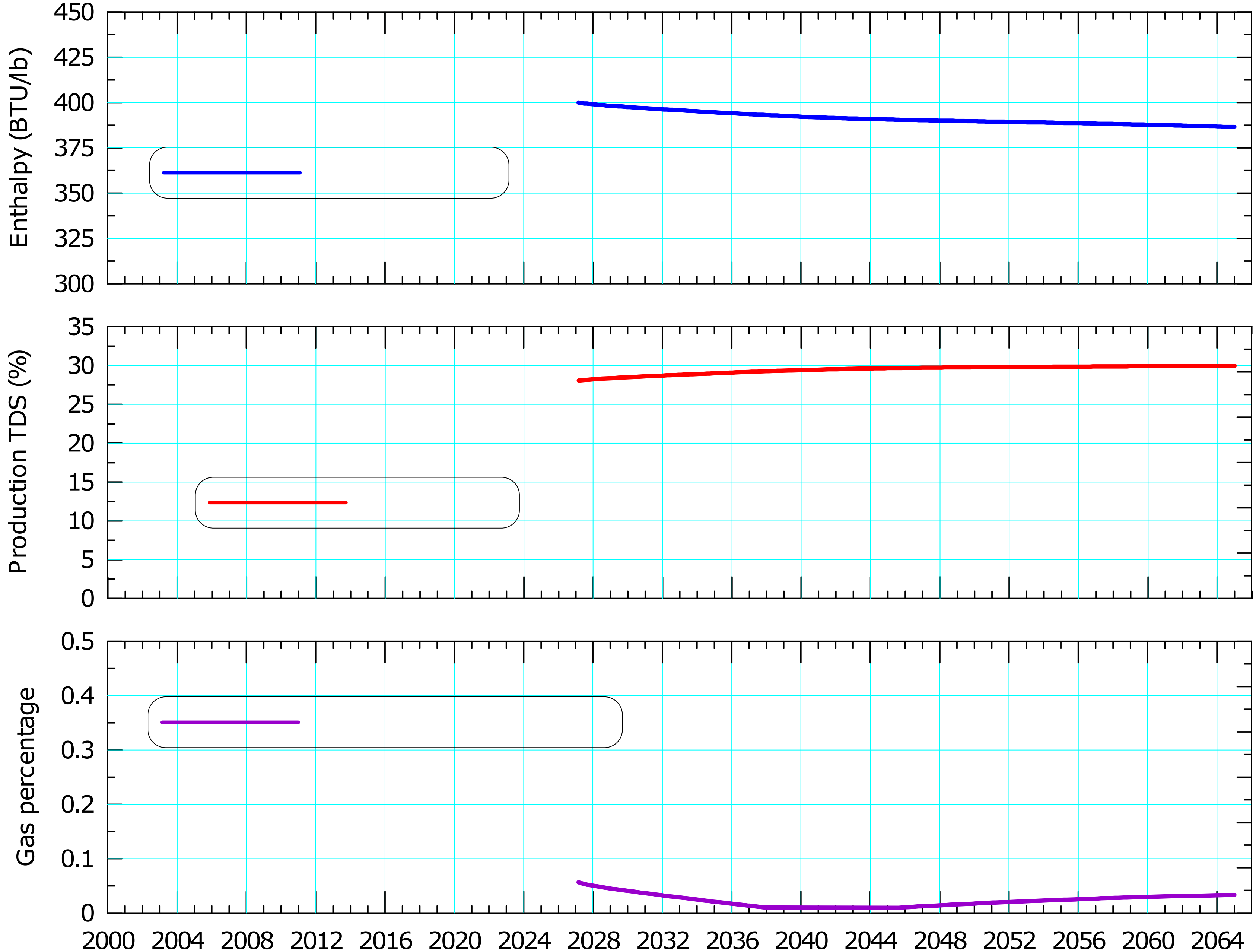

Figure 3.3 Forecast of Enthalpy, TDS and NCG for Elmore North

GeothermEx

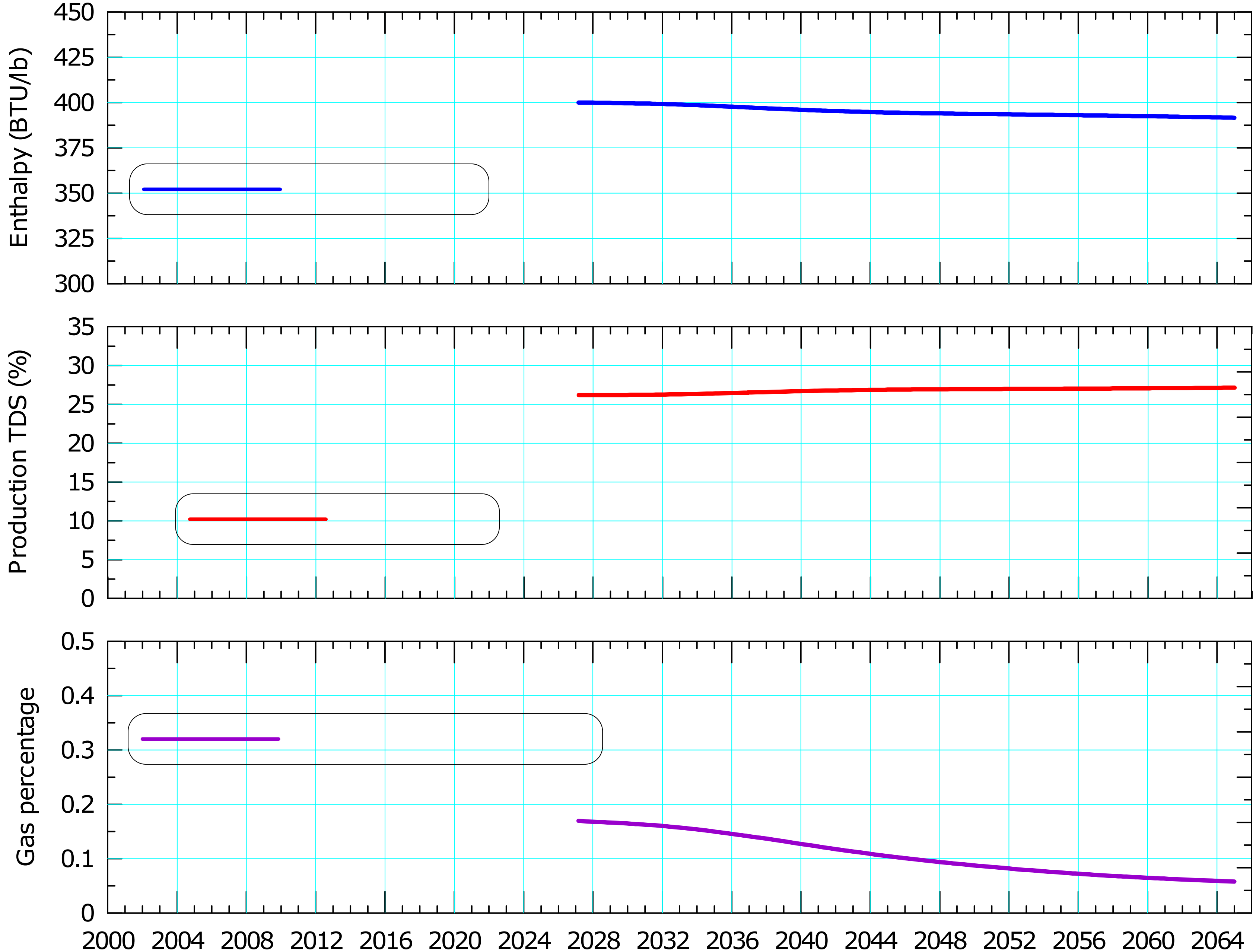

Figure 3.4 Forecast of Enthalpy, TDS, and NCG for Morton Bay

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