PROCEEDINGS, 48th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 6-8, 2023
SGP-TR-224

GeoLingo: Defining Optimal Data Collection Requirements for Geothermal Operations and Advanced Analytics

Andrew Marsh, Paul Siratovich, Nicole Taverna, Grant Buster, Jon Weers, Iraklis Konstantopoulos and Andrea Blair

Upflow, Ltd., PO Box 61, Taupō 3330, New Zealand
National Renewable Energy Laboratory (NREL), 15013 Denver West Parkway, Golden, CO 80401 USA

andrew.marsh@upflow.nz, paul.siratovich@upflow.nz, nicole.taverna@nrel.gov, grant.buster@nrel.gov, jon.weers@nrel.gov, hercules@upflow.nz, andy.blair@upflow.nz

Keywords: data, instrumentation, compression, conditioning, machine learning, advanced analytics, integrated modeling, GOOML

ABSTRACT

This paper sets out what we view to be the optimal data collection schema to enable effective data-driven decision making in geothermal operations. The focus is on the performance of an overall geothermal system comprising reservoir, steam field gathering, power plant units, and injection; rather than sub-systems of the power plants. An overall system dataset including power plant performance at the unit level is sufficient to feed models that can give valuable insights for real-world operations.

Data collection requirements have been set out for different types of geothermal systems including steam, two-phase, and liquid-dominated wells. The two main types of power plant are covered, flash and binary. Suggested resolution and intervals of measurement are provided with rationale for how such volumes of collected data would be useful.

The intent of this paper is to offer guidance to future or expanding geothermal developments by providing a minimum set of instrumentation and monitoring requirements that will allow operators to use advanced analytics. It may also serve as a useful guide when considering retrofitting and upgrading existing plant. Retrofitting instrumentation will yield gains where any previous efforts to optimise existing facilities have been frustrated through lack of data. Improvements in sensor technologies, algorithms and software make resolving gaps in the data increasingly attractive over time.

This paper leverages the GOOML project (Geothermal Operations Optimisation through Machine Learning (see Buster et al, 2021)) where experimentation with machine learning algorithms has informed what is and is not possible to optimise given certain data inputs. Data treatment and conditioning pitfalls are also explored to facilitate upfront design of analytical routines. The benefits from big-data analytics can only be realised if data is collected from the right places with sufficient resolution to allow the algorithms to develop an accurate representation of the state of the system and how it is evolving.

INTRODUCTION

The process to harness geothermal energy and convert it to electricity and other useful outputs has been around for decades and there now exists more than 15,960 MWe of installed capacity at geothermal plants worldwide (IRENA, 2021). Despite the large number of facilities, no two are exactly alike. This is due to a combination of factors: varying topography of the geothermal field, locations of individual wells, and technological improvements over time that have seen ever-increasing unit sizes for power production.

However, commonality emerges when geothermal production systems are broken down into their constituent parts. Most geothermal systems can be represented by combinations of the top 10 most common components: wells, pipelines, pumps, turbines, heat exchangers, condensers, valves, separators, cooling towers, and gas extractors. By laying out instrumentation schemata for common arrangements of these top-ranked components we intend to provide designers and developers an outline of how to generate the critical data sets for optimisation and management of assets.

For existing installations that fall short of these instrumentation standards, these schemata offer a retrofitting opportunity to generate the missing datasets. Once this data is being collected, it is then possible to generate operating insights, prioritise opportunities, and execute projects to realise additional value from geothermal infrastructure.

DEFINITIONS

This paper is arranged as a series of schemata and tables covering the primary components of typical geothermal operational systems. The paper will intentionally avoid detailed specifications for instruments allowing for future improvements in sensors.

For example, chemistry is typically collected as fluid samples and taken away for analysis at a lab. In the future, these methods may be replaced by online meters should the accuracy, maintainability and cost of such meters improve. Also, research and development into advanced sensor applications such as two-phase flow measurements or well logging may yield increased accuracy and/or frequency of measurements.

The focus of this paper will be on providing a physical understanding necessary to support optimisation. Each data point specified will therefore be accompanied by a rationale for collection, a resolution and interval to attempt to set a minimum standard that creates a physical understanding or a basic digital twin for the overall system. Suggested values for resolution should be considered a starting point only and be fine-tuned according to instrument capabilities and noise considerations.

Note that this paper is not intended to inform design considerations outside of minimum instrumentation for optimisation and monitoring purposes. Control loops and safety functions will require additional instruments. Placement of valves and other equipment is for illustration only and not intended to represent a fully designed system.

DATA TREATMENT AND COMPRESSION

Collection of operating data into a Supervisory Control and Data Acquisition (SCADA) system and then into a Historian for storage is a fundamental organisational and structural data processing step that influences what can be done thereafter. By design, these systems modify and reduce the resolution of historical data with varying intents. It is important to ensure that the flow of relevant metadata and relationship structures is preserved or enhanced as part of data collection.

Data compression is an essential process for preserving meaningful data and filtering out the irrelevant to speed up processing of multiyear historical data. Data compression settings, such as the minimum value change required before the next value is stored, need careful attention to preserve useful data from transient operations and other trends over a longer timeframe. Data collected at one second intervals may be very informative for start-up operations or where higher frequency oscillations are occuring (such as slugging or surging two-phase flow) but most of the steady-state operating data in geothermal baseload power generation can be omitted. A good data compression algorithm and setup will aim to collect information at intervals as frequent as suggested in the figures and tables later in this paper while the system is undergoing a transient or upset condition. It will also aim to omit data points that are just noise during steady state operation. Setting appropriate resolutions requires making a trade-off between the risk of missing key information and potentially storing too much data for later processing. Regular review of data compression performance in the real-world operating environment is an essential step in preparing for data analytics.

It is also important from the outset to understand and curate relationships where different instruments may describe the same piece of equipment. This allows intelligent data compression as well as identification of events and additional metadata collection (such as limits and alarms), and timestamps for changes made to plant configurations. Going back and identifying such changes from the raw data and logbooks is incredibly tedious and can lead to multiple versions of the truth so any effort to code this into the collection system upfront is worthwhile.

Ideally, no manual manipulation of data would be required. But it is hard to foresee all potential data errors. Sometimes an instrument is miscalibrated and the data needs to be corrected to be useful. Such quality assurance processes with the data require good practices in data manipulation (e.g., automatically maintaining a record of changes made) and preservation of a single source of truth.

INSTRUMENTATION SCHEMATA

Figure 1 below illustrates how the subsequent schemata relate to one another.
Figure 2 sets out a key to symbols used in the following figures that are not labelled. Subsequent figures and the associated tables then outline the standard instrumentation suggested for each schema, including measurement location, purpose, resolution, interval, and rationale.

Figure 1: Diagram showing schemata relationships

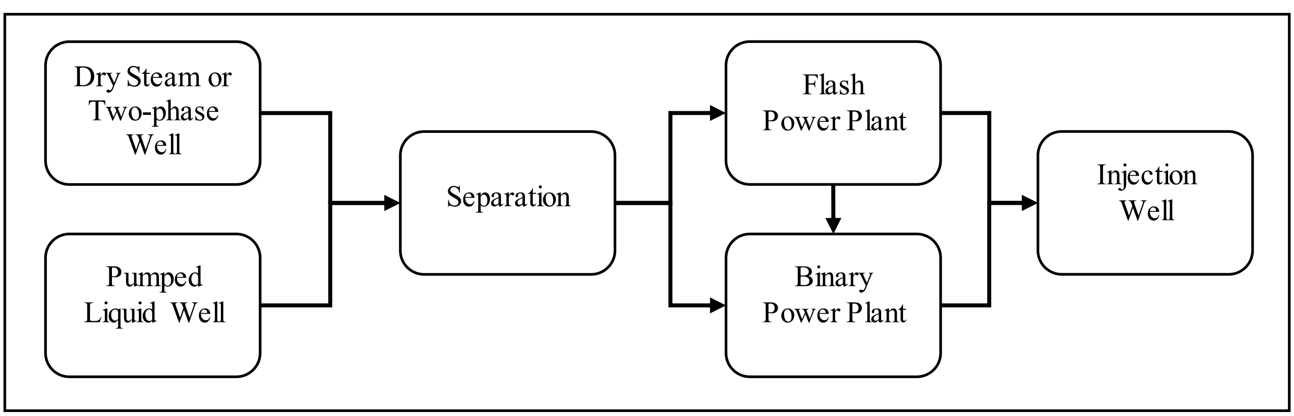


Figure 2: Key to symbols used in following schema

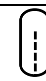
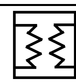
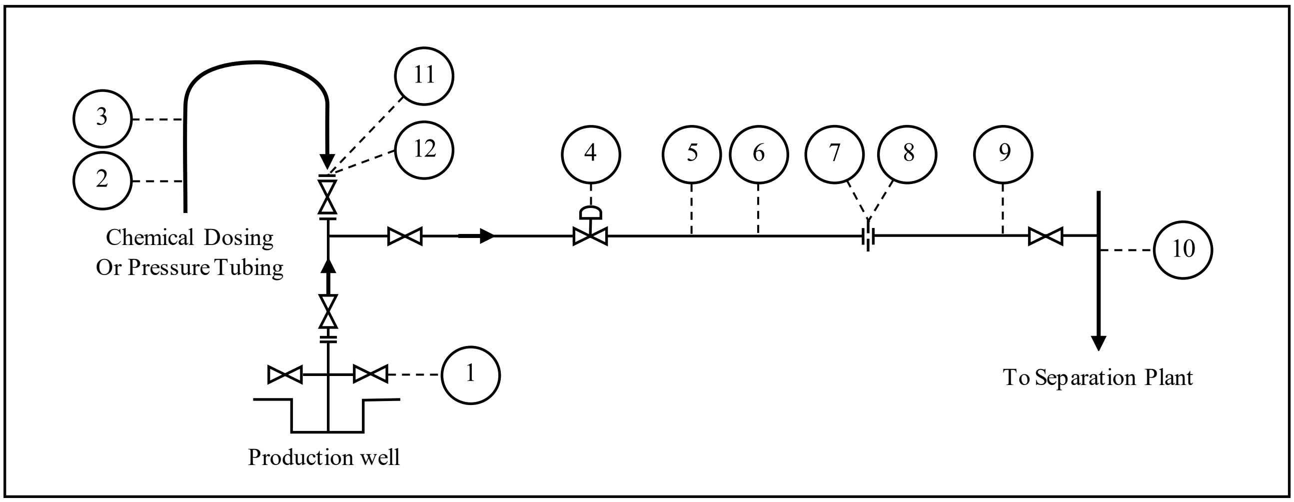
Pipeline (with flow direction)		Steam Separator	
Control Valve		Brine Accumulation Tank	
Isolation Valve (for reference)		Orifice Plate (or other flow measurement device)	
Heat Exchanger		Fluid Pump	

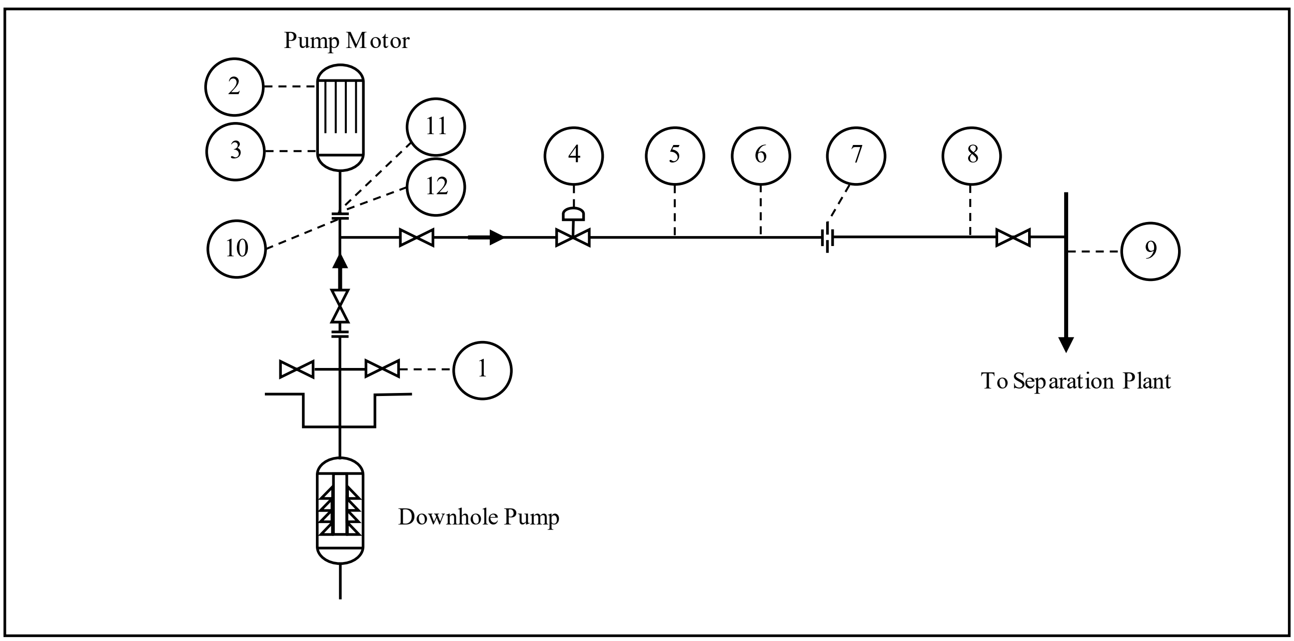
Figure 3: Dry steam and two-phase well instrumentation and table of measurement points



Location	Type	Purpose	Resolution	Interval	Resolution/Interval Rationale
1	Well Head Pressure	Well Performance, Safety	0.01 bar (0.1 psi)	1 sec	Monitor transients in well operation (e.g. start-up), real-time notification of abnormal well behaviour
2	Flow	Chemical dosing quality assurance	0.1 kg/s (1 kph)	1 min	Minimise exposure time for dosing problems, monitor desired dosing rates
3	Pressure	Detect problems with delivery of chemicals (e.g. broken tube, blockages), downhole pressure monitoring	0.1 bar (1 psi)	1 min	Minimise downtime for dosing problems, assist failure diagnosis
4	Valve Position	Control, Well Performance, Problem Diagnosis	0.1%	1 sec	Correlate changes in valve opening with changes in well state/performance
5	Temperature	Determine superheat/enthalpy (for Dry Steam wells)	0.1 ˚C (0.2 ˚F)	1 sec	Monitor performance during transients in well operation (e.g. start-up)
6	Pressure	Upstream pressure for flow measurement, pressure drop across control valve and wellhead	0.01 bar (0.1 psi)	1 sec	Monitor performance during transients in well operation (e.g. start-up)

7	Flow	Well delivery performance	0.1 kg/s (1 kph)	1 sec	Monitor performance during transients in well operation (e.g. start-up)
8	Enthalpy	Measure Enthalpy (for Two-phase wells)	1 kJ/kg (0.5 Btu/lbm)	1 min - 3 months	Ideally this would be measured continuously to plot well performance changes, if by chemical means (TFT) then 3 months intervals
9	Chemistry	Geochemistry (fluid origin), scaling potential and plant chemistry	ppb	3 - 6 months	Sampled at an interval that allows early detection of fluid evolution trends. If chemistry is stable, interval can be extended. If transient, the particular well should be measured more frequently.
10	Pressure	Determine pressure drop in branch line and main production lines	0.01 bar (0.1 psi)	1 sec	Transient performance (e.g. slugging, surging)
11	PTS log	Pressure, Temperature, Spinner (flow) for well bore modeling and feedzone characterisation	0.1 m (0.5 ft)	1-3 years	Alternate flowing PTS and shut-in PTS as beneficial. Sampled at an interval that allows up-to-date characterisation. If performance is stable, interval can be extended. If transient, the well should be measured more frequently.
12	Caliper, casing condition logs	Well integrity, well bore restrictions	0.1m (0.5 ft)	2-10 years	Establish a baseline and monitor at intervals according to threat levels. Updates risk to the producing asset and fluid supply.

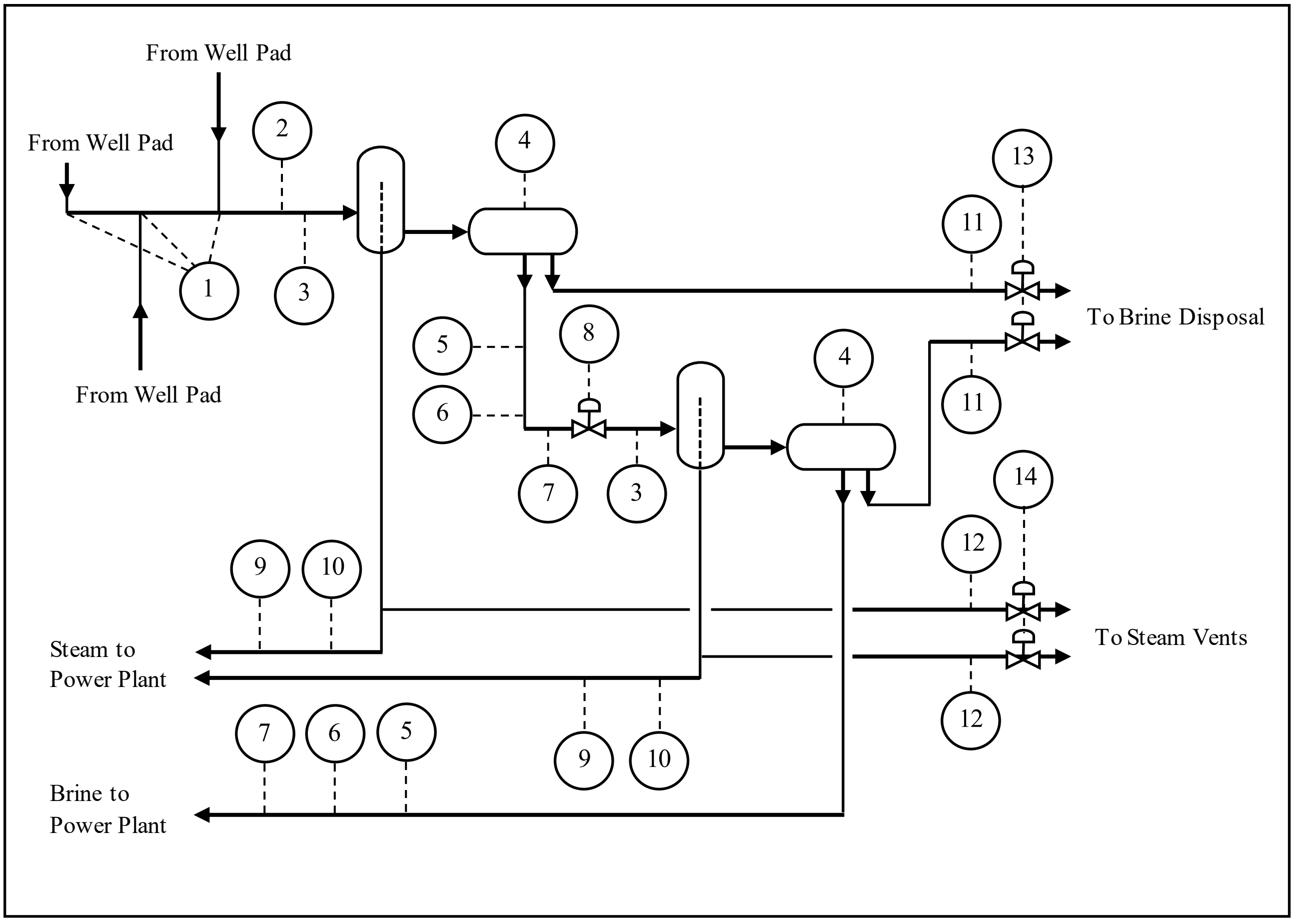
Figure 4: Pumped liquid well instrumentation and table of measurement points



Location	Type	Purpose	Resolution	Interval	Resolution/Interval Rationale
1	Well Head Pressure	Well Performance, Safety	0.01 bar (0.1 psi)	1 sec	Monitor transients in well operation (e.g. start-up), real-time notification of abnormal well behaviour

2	Speed	Motor/pump rotational speed indicates performance	1 rpm	1 sec	Determine pump performance, assist failure diagnosis, real-time notification of operations outside of normal
3	Power	Motor/pump power indicates performance	0.1 kW (0.1 bhp)	1 sec	Determine pump performance, assist failure diagnosis, real-time notification of operations outside of normal
4	Valve Position	Control, Well Performance, Problem Diagnosis	0.1%	1 sec	Correlate changes in valve opening with changes in well state/performance
5	Temperature	Determine enthalpy, energy balance	0.1 ˚C (0.2 ˚F)	1 sec	Monitor performance during transients in well operation (e.g. start-up)
6	Pressure	Upstream pressure for flow measurement, pressure drop across control valve and wellhead	0.01 bar (0.1 psi)	1 sec	Monitor performance during transients in well operation (e.g. start-up)
7	Flow	Well delivery performance	0.1 kg/s (1 kph)	1 sec	Determine pump performance, assist failure diagnosis, long-term performance
8	Chemistry	Geochemistry (fluid origin), scaling potential and plant chemistry	ppb	3 months - 6 months	Sampled at an interval that allows early detection of fluid evolution trends. If chemistry is stable, can be extended. If transient, the well should be measured more frequently.
9	Pressure	Determine pressure drop in branch line and main production lines	0.01 bar (0.1 psi)	1 sec	Transient performance (e.g. slugging, surging)
10	Level	Determine liquid level in the wellbore while static (bubbler tube or otherwise)	1 m (3 ft)	1-3 months	To indicate evolution of pressure in the local reservoir
11	PTS log	Pressure, Temperature, Spinner (flow) for well bore modeling and feedzone characterisation	0.1 m (0.5 ft)	1-3 years	Alternate flowing PTS and shut-in PTS as beneficial. Sampled at an interval that allows up-to-date characterisation. If performance is stable, interval can be extended. If transient, the well should be measured more frequently.
12	Caliper, casing condition logs	Well integrity, well bore restrictions	0.1 m (0.5 ft)	2-10 years	Establish a baseline and monitor at intervals according to threat levels. Updates risk to the producing asset and fluid supply.

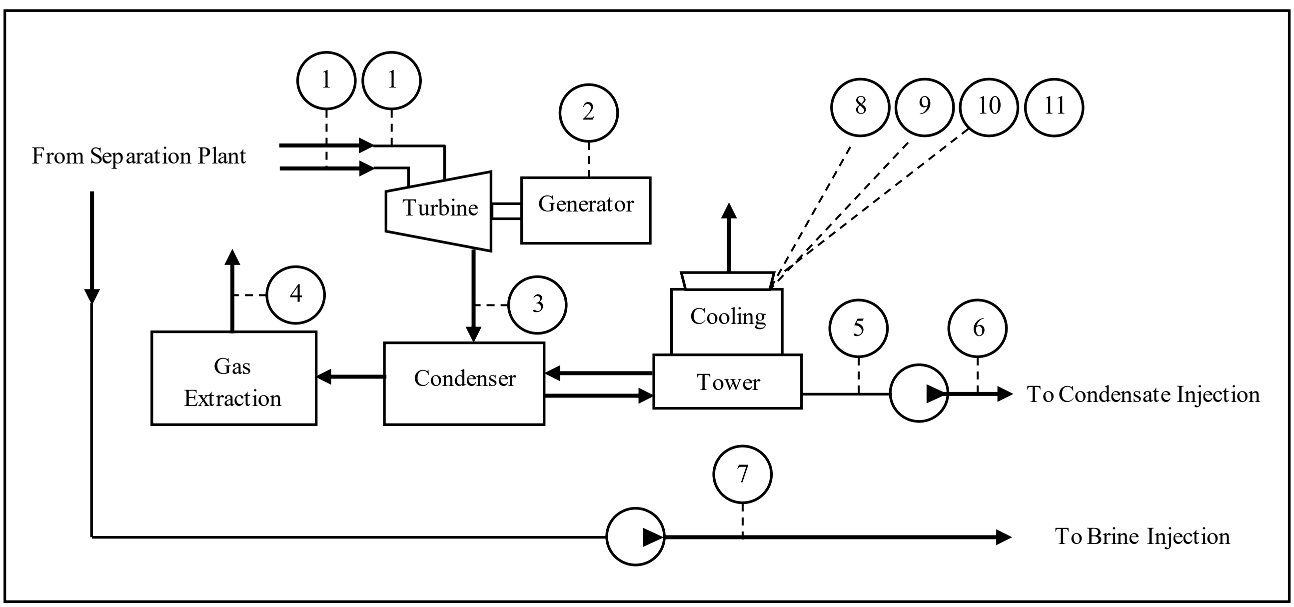
Figure 5: Centralised multi-flash separation instrumentation and table of measurement points



Location	Type	Purpose	Resolution	Interval	Resolution/Interval Rationale
1	Pressure	Determine pressure drop in branch line and main production lines (measured at every junction)	0.01 bar (0.1 psi)	1 sec	Transient performance (e.g. slugging, surging)
2	Temperature	Determine superheat/enthalpy (for Dry Steam wells)	0.1 ˚C (0.2 ˚F)	1 sec	Monitor performance during transients in well operation (e.g. start-up)
3	Pressure	Pressure at inlet to separator	0.01 bar (0.1 psi)	1 sec	Separator performance and monitoring plant transients (e.g. start-up, slugging, surging)
4	Level	Liquid level in accumulator	1%	1 sec	Safety functions, transients (e.g. start-up, slugging, surging), mass balance adjustment to liquid flow meters
5	Pressure	Brine pressure head from accumulators	0.01 bar (0.1 psi)	1 sec	Monitor transients (e.g. start-up, slugging, surging), troubleshooting unsteady flow, flashing
6	Flow	Mass balance	0.1 kg/s (1 kph)	1 sec	Coupled with accumulator to provide liquid mass balance for the rest of the system

7	Chemistry	Scaling potential and plant chemistry	ppb	3 months - 6 months	Sampled at an interval that allows early detection of fluid evolution trends. If chemistry is stable, can be extended. If transient, this should be measured more frequently.
8	Valve Position	Level control in upstream separation	0.1%	1 sec	Diagnosis and stability in the separation system
9	Steam Pressure	Determine separator pressure drops and turbine system pressures	0.01 bar (0.1 psi)	1 sec	Turbine performance and plant transients (e.g. start-up, slugging, surging)
10	Steam Flow	Mass balance, turbine performance	0.1 kg/s (1 kph)	1 sec	Turbine performance and plant transients (e.g. start-up, slugging, surging)
11	Dump Flow	Mass balance	0.1 kg/s (1 kph)	1 sec	Coupled with accumulator to provide liquid mass balance to rest of the system, upset conditions
12	Vent Flow	Mass balance, turbine performance	0.1 kg/s (1 kph)	1 sec	Turbine performance and plant transients (e.g. steam pressure control)
13	Dump Valve Position	Mass balance and event diagnosis	1%	1 sec	Event analysis, upset conditions, mass balance confirmation
14	Vent Valve Position	Mass balance and event diagnosis	1%	1 sec	Event analysis, upset conditions, mass balance confirmation

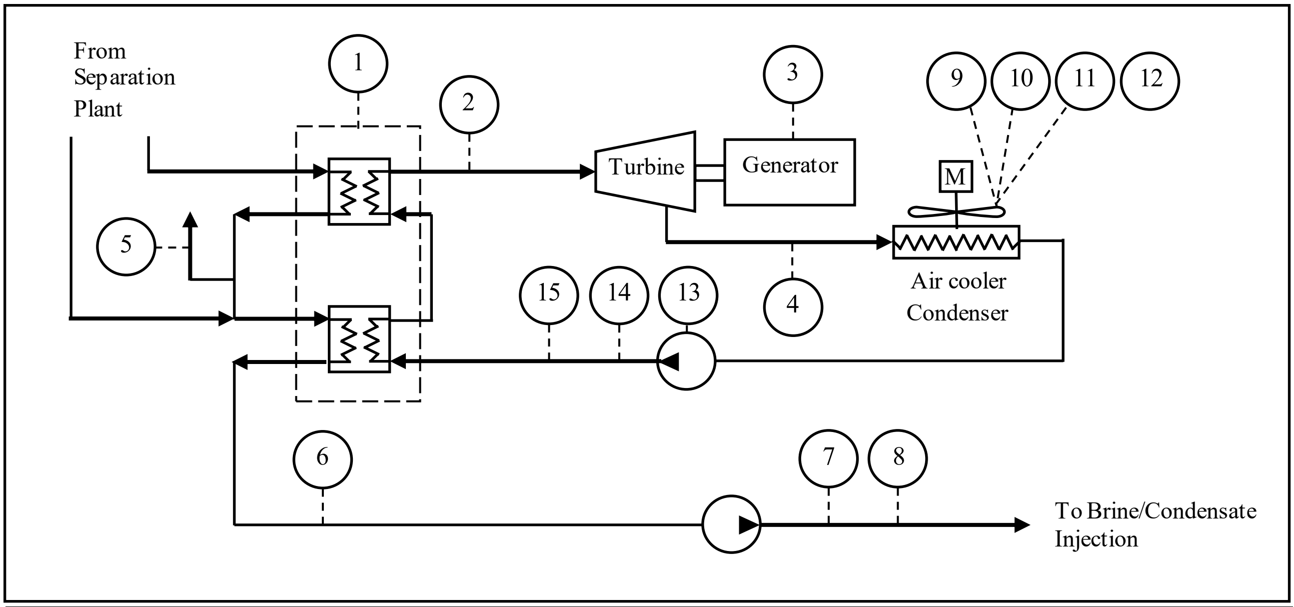
Figure 6: Flash power plant instrumentation and table of measurement points



Location	Type	Purpose	Resolution	Interval	Resolution/Interval Rationale
1	Turbine Inlet Pressure	Turbine performance, scaling (located after turbine control valves)	0.01 bar (0.1 psi)	1 sec	Capturing start-up transients, variations in ambient conditions and efficiency changes

2	Generator Power	Turbine performance	1 kW (1 bhp)	1 sec	Capturing start-up transients, variations in ambient conditions and efficiency changes
3	Condenser Pressure	Turbine performance, cooling system performance	0.01 bar (0.1 psi)	1 sec	Capturing start-up transients, variations in ambient conditions and efficiency changes
4	Non-Condensable Gas Flow	Emissions monitoring, turbine and gas extraction performance	0.1 kg/s (1 kph)	1 sec	Capturing start-up transients, variations in ambient conditions and efficiency changes
5	Condensate Flow	Mass balance, injection performance	0.1 kg/s (1 kph)	1 sec	Cooling water consumption, level control troubleshooting, condensate injection demands
6	Pressure	Condensate system performance	0.01 bar (0.1 psi)	1 sec	Cooling water consumption, level control troubleshooting, condensate injection demands
7	Pressure	Brine Injection System	0.01 bar (0.1 psi)	1 sec	Injection capacity, performance of injection pumps, transients (e.g. start-up), scaling
8	Ambient Dry-Bulb Temperature	Cooling system performance	0.1 ˚C (0.2 ˚F)	1 min	Sample changes over time at varying ambient conditions
9	Ambient Pressure	Cooling system performance	1 hPa (0.01 psi)	1 min	Sample changes over time at varying ambient conditions
10	Relative Humidity	Cooling system performance	1 %	1 min	Sample changes over time at varying ambient conditions
11	Power	Parasitic loads for net power calculation	1 kW (1 bhp)	1 sec	To determine overall power conversion efficiency

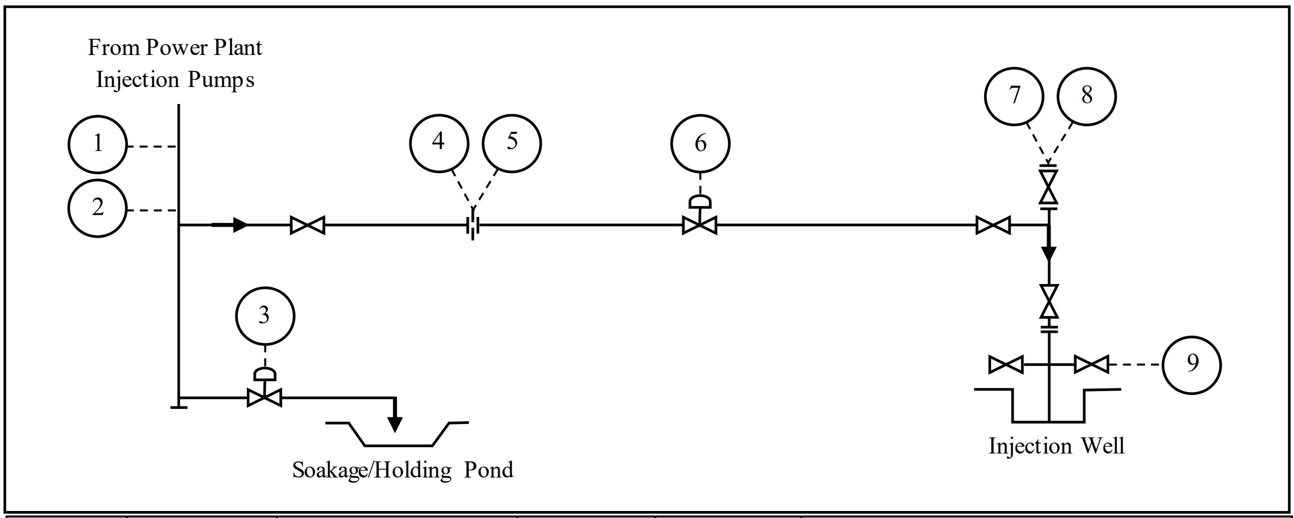
Figure 7: Binary power plant instrumentation and table of measurement points



Location	Type	Purpose	Resolution	Interval	Resolution/Interval Rationale
1	Performance	Heat exchanger performance (requires sufficient instruments for a heat and mass balance – differential pressures, temperatures, flows for both fluid streams)	-	1 sec	Determine heat exchange performance for early detection of cleaning, predicting generation output, cycle performance diagnosis
2	Vaporiser Pressure	For binary turbine performance	0.01 bar (0.1 psi)	1 sec	Cycle performance diagnosis
3	Generator Power	For binary turbine performance	1 kW (1 bhp)	1 sec	Output and fault detection information
4	Condenser Pressure	Turbine performance, cooling system performance	0.01 bar (0.1 psi)	1 sec	Cycle performance diagnosis, variation due to ambient conditions
5	Non-Condensable Gas Flow	Emissions monitoring, heat exchange performance	0.1 kg/s (1 kph)	1 sec	Upset and off-design conditions monitoring, transients in well operation (e.g. start-up), mass balance adjustment
6	Pressure	Plant back-pressure, avoidance of flashing conditions	0.01 bar (0.1 psi)	1 sec	Upset and off-design conditions monitoring
7	Flow	Condensate + Brine flow rate	0.1 kg/s (1 kph)	1 sec	Monitor performance during transients in well operation (e.g. start-up)
8	Pressure	Injection pressure	0.01 bar (0.1 psi)	1 sec	Injection capacity, performance of injection pumps, transients (e.g. start-up), scaling
9	Ambient Dry-Bulb Temperature	Cooling system performance	0.1 ˚C (0.2 ˚F)	1 min	Sample changes over time at varying ambient conditions

10	Atmospheric Pressure	Cooling system performance	1 hPa (0.01 psi)	1 min	Sample changes over time at varying ambient conditions
11	Relative Humidity, Wind direction	Cooling system performance	1%, 1°	1 min	Sample changes over time at varying ambient conditions
12	Power	Parasitic loads for net power calculation	1 kW (1 bhp)	1 sec	To determine overall power conversion efficiency
13	Motive Fluid Pump Power	Cycle analysis, pump performance, Parasitic load for net power calculation	1 kW (1 bhp)	1 sec	To determine overall power conversion efficiency, cycle analysis, troubleshooting, pump cavitation issues
14	Pressure	Cycle analysis, pump performance	0.01 bar (0.1 psi)	1 sec	Cycle analysis, troubleshooting, pump cavitation issues
15	Flow	Motive fluid cycle analysis	0.1 kg/s (1 kph)	1 sec	Cycle analysis, troubleshooting

Figure 8: Injection well instrumentation and table of measurement points



Location	Type	Purpose	Resolution	Interval	Resolution/Interval Rationale
1	Pressure	Determine pressure drop in branch line and main injection lines	0.01 bar (0.1 psi)	1 sec	Transient performance (e.g. slugging, surging, flashing), scaling
2	Temperature	Injection temperature for well and reservoir performance modeling	0.1 ˚C (0.2 ˚F)	1 sec	Monitor performance during transients in well operation (e.g. start-up)
3	Valve Position	Detect injection diversion to pond for mass balance	1%	1 sec	Determine any times when full injection is not occurring, upsets

4	Pressure	Upstream pressure for flow measurement, pressure drop across control valve and wellhead	0.01 bar (0.1 psi)	1 sec	Monitor performance during transients in well operation (e.g. start-up)
5	Flow	Well injection performance	0.1 kg/s (1 kph)	1 sec	Monitor performance during transients in well operation (e.g. start-up)
6	Valve Position	Control, well performance, problem diagnosis	1%	1 sec	Correlate changes in valve opening with changes in well state/performance
7	PTS log	Pressure, Temperature, Spinner (flow) for well bore modeling and characterisation	0.1 m (0.5 ft)	1-3 years	Alternate flowing PTS and shut-in PTS as beneficial. Sampled at an interval that allows up-to-date characterisation. If performance is stable, interval can be extended. If transient, the well should be measured more frequently.
8	Caliper, casing condition logs	Well Integrity, well bore restrictions	0.1m (0.5 ft)	2-10 years	Establish a baseline and monitor at intervals according to threat levels. Updates risk to the producing asset and fluid supply.
9	Well Head Pressure	Well Performance, Safety	0.01 bar (0.1 psi)	1 sec	Monitor transients in well operation (e.g. start-up), real-time notification of abnormal well behaviour

FURTHER MEASUREMENTS

The schemata provided in the figures above will not provide for all possible performance evaluations or special configurations. It is good practice to receive positional feedback from all actuated valves and ideally from any manual valves used to put a piece of equipment into service (such as a branch pipeline). Having direct feedback from manual valves positions is far more reliable than inferring these from physical values such as pressures or from logbook entries.

It is also good practice to collect enough pressure, temperature and flow rate information to be able to ascertain the state of the fluid at all parts of the system that are separated by items of major equipment. While this is not always necessary as shown in the schemata above, if in doubt, it is better to put in a measurement during design rather than regret or retrofit it later. Where the saturation state of the fluid is known then temperature is often omitted since pressure and temperature are related – however, caution should be used where high amounts of geothermal gases in the fluid can distort these relationships.

There are a number of reasons for collecting data from more locations where the geothermal system or infrastructure has been evaluated to carry higher risks. This might include the use of a new piece of equipment, an unproven arrangement, a particular concern for the geothermal resource arising from exploration or modelling or an environmental vulnerability. Some examples have been listed below:

- Separator Performance and Steam Purity – where carryover of oversaturated minerals in the brine is a potential issue for turbines or heat exchangers
- Scaling in pipelines – where accumulation of scale on pipe walls may increase pressure drops and reduce flows
- Corrosion – where the chemistry may challenge the materials used for construction
- Where there is low water availability and/or restrictions on water use
- Issues with soakage of geothermal fluids to ground and therefore systems to transfer cold geothermal brines for injection/disposal and pond management
- Treatment or disposal of geothermal gases
- Cooling tower biological control

CONCLUSION

We hope that the information presented in this paper will provide design engineers and operators with a useful guide for setting out measurement points in geothermal power plant operations that support performance analytics and effective data-driven decision making. Data collected from the right places with sufficient resolution allows algorithms to develop accurate representations of system components and how these have changed over time. By combining this knowledge into a system-wide performance model through process simulators like GOOML, the benefits from big-data analytics can boost operating performance significantly over the lifetime of the plant.

ACKNOWLEDGEMENTS

Thank you to our commercial partners, Contact Energy Limited, Ngati Tuwharetoa Geothermal Assets Limited, and Ormat Technologies, Inc., for their support of this project.

This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Geothermal Technology Office Award Number DE-EE0008766. This work was authored by Upflow, Ltd. and the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308 with funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy (EERE) Geothermal Technologies Office (GTO). The views expressed in the article do not necessarily represent the views of the DOE or the United States Government. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a nonexclusive, paid- up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for United States Government purposes.

REFERENCES

Buster, G., Siratovich, P., Taverna, N., Rossol, M., Weers, J., Blair, A., Huggins, J., Siega, C., Mannington, W., Urgel, A., Cen, J., Quinao, J., Watt, R., and Akerley, J. A New Modeling Framework for Geothermal Operational Optimization with Machine Learning (GOOML), *Energies* **14, no. 20: 6852** (2021). https://doi.org/10.3390/en14206852.

IRENA (2022), Renewable Energy Statistics 2022, The International Renewable Energy Agency, Abu Dhabi