DOUBLE-SIDED CAUSER PAYS FOR PRIMARY FREQUENCY RESPONSE

A CS Energy Sponsored Research Project

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FINAL REPORT

IES Intelligent Energy Systems

Executive Summary

This is the report of a project to define and implement a substantial prototype system for paying for and allocating the costs of Primary Frequency Response, or PFR. PFR is the relatively Fast acting response, roughly proportional to frequency deviation, which synchronous generators have traditionally provided to the electricity system.

In recent years the system has lost much of this capability precipitated by synchronous generator retirements and several regulatory enforcement actions. The aim of this project has been to demonstrate a workable and viable means to incentivise the provision of PFR in a commercial manner. As a practical matter, it can complement and not compete with the Rule Change for mandatory provision of PFR that is passing through AEMC's processes at the time of writing, with a Final Determination expected on 26 March 2020.

To help promote informed debate, IES is prepared to make available online a set of reports (mostly charts) illustrating the outcome of these calculations to interested parties. We will also be prepared to present to regulators, market operators and policymakers.

This project implements a version of deviation pricing stripped down to deal specifically with primary frequency control and closely aligned to the approach used in regulation causer pays. IES has undertaken a great deal of internal research into a more general system that can also deal with inertia and fast frequency response as well as the slower acting components of FCAS. It continues to seek financial support from market operators, rule-makers, participants and ARENA to fully document and publish the theory, to demonstrate the approach through simulations, develop prototype metering and control arrangements and to undertake trials.

IES would like to thank CS Energy and its staff for their foresight in sponsoring and providing input into this and earlier related projects over a period of several years.

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1 Introduction

In a 2017 project, CS Energy (CSE) commissioned IES to develop a package of improvements to the NEM auction[1]. This package included an improved mechanism for pricing and allocating the costs of frequency control, potentially for regulation, contingency services and other services such as fast frequency response and inertia not presently supported in the current NEM market rules.

In the intervening few years, events in the market have further highlighted the need for improvements in this area. Specifically, AEMO has been working to improve regulation performance through tuning of the AGC system and adjusting the causer pays incentive mechanism. The AEMC is now considering a rule change proposal from AEMO that would mandate a capability to provide Primary Frequency Response (PFR) and reward parties who provide PFR by exempting them from causer pays. In December 2019 AEMC issued a Draft Determination which would essentially accept AEMO's arguments for mandating a requirement to be capable of PFR, but which also laid the groundwork for improved incentive arrangements in the future.

As a key participant in the energy market CS Energy (CSE) wishes to promote a more efficient approach along the lines of the 2017 IES report. In 2019 CSE commissioned IES to implement CSE's estimate of the cost of PFR provision, the results of which have been presented to AEMC and which are published on IES's NEO-Point[2]. CSE now wishes to operationalise this estimate to be like the causer pays mechanism used for regulation, an option offered by the AEMC in its discussion paper on the AEMO proposals[3]. However, there will be significant differences in the approaches as there is no enablement market for PFR, so the payments and charges will have to be two or double-sided in the PFR case, in contrast to the one-sided approach used in regulation.

The remainder of this report is in three parts:

- In Section 2 we step through the design issues we faced when developing the logic behind the system. There may be some elements of this logic that are contentious. We have tried to address these elements where possible within this report and as options in the presentational charts to be provided online.
- In Section 3 we describe the details of our implementation of the PFR Double Sided Causer Pays System. The system is intended for demonstration and valuation purposes and is not complete in every respect. For example, we have not covered off islanded situations although that would not be unduly difficult to deal with.
- Appendix A contains the mathematical detail and an outline of the reporting that can be made available online through NEO-Point.

[1] *A Package Of Improvements for the NEM Auction: A Report Prepared by Intelligent Energy Systems For CS Energy* - 18 April 2017. Available on request from IES.

[2] *Costing of Primary Frequency Control: Report to CS Energy* -6 August 2019. Available on request from IES.

[3] *Primary frequency response rule changes, Consultation paper*, AEMC, 19 September 2019, p78, Option F.

2 Design Issues

In this section we provide an outline of the main design issues addressed during the project. It is essentially an overview of the much greater detail provided in the Appendix.

2.1 Role of ACE-REG

AEMO's frequency control system aims to keep frequency within defined bounds, those bounds being set by the Reliability Panel. To do this, AEMO tracks a quantity known as Area Control Error - Regulation ('ACE-REG'), which is an estimate of how much additional (or less) power injection is needed to bring the system back into balance at 50Hz. While this quantity in AEMO's system contains a small component of time error and some other adjustments, and is subject to AEMO's tuning over time, for the purposes of this project we will take ACE-REG to be directly proportional to frequency deviation or error i.e.

ACE-REG(in MW) = - Constant x Frequency_Deviation (in Hertz)

The constant in recent times has been set at 2800MW/Hz. The negative sign means that the requirement is positive if the frequency deviation is negative, and vice versa.

The variable ACE is the negative of ACE-REG and is an estimate of the current MW shortfall. It can also be viewed as the load relief automatically delivered (arising from minor perturbations on the system and AEMO 5 minute demand forecast error) by unscheduled parties when scheduled generation and demand do not align at 50Hz. It is also linked to the amount of proportional governor response freely available in the system. There is circularity between what is being incentivised (correction of frequency error through primary governor control) and the size of the error for a given change in frequency. As will be explained, the aim of this project is to measure the response of units and pay them for it; we assume that this is presently accounted for in the SCADA measurements and ACE is solely attributed to load relief. This assumption may be reviewed with the implementation of mandatory primary frequency control from October 2020. This is further discussed in section 2.5 and equations 13.2 and 13.3 of the Appendix.

ACE and ACE-REG are calculated from frequency deviations measured at 4-second intervals by AEMO's SCADA system. All the calculations described in this section are performed at this level and finally summarised in 5 minute values for presentation and analysis.

2.2 Distinguishing Raise and Lower

As for other forms of FCAS, we distinguish raise and lower services for PFR. The reason for doing so is that the technologies and cost structures for raise and lower may differ significantly. Whether this difference is enough to justify separate treatment is a commercial decision and was determined by CSE in the development of the efficient cost estimate explained in section 1 above. It is not addressed in this project. With raise and lower separately distinguished, we note that raise applies when ACE-REG is positive and lower applies when ACE-REG is negative.

2.3 Performance Baseline

To measure performance in contributing to PFR or causing the requirement for PFR, we need a defendable baseline. For scheduled units, that baseline for Regulation Causer Pays is the linear trajectory determined by the current state of the unit and the target set in the energy market. We propose the same for PFR Causer Pays.

We also considered several other options to address a possible criticism that units paid under PFR Causer Pays would be "double dipping" if they were also enabled and paid in the Regulation enablement market. The AEMC raised this issue in its Frequency Control Arrangements Review Final Report[4]. These options are outlined in the Appendix and the outcomes from using them can be viewed as options on some of the published charts.

We recommend against attempting to net out enabled regulation for the following reasons:

- the possible ways of doing so are complicated, ambiguous and, in the end, illogical;
- the fear of double payment is overblown, considering the competitive pressures that would be at work on regulation enablement if performance is also paid; and
- arrangements for payment at different timescales for the same deviations are consistent with a theoretical analysis of the control task.

To illustrate the last point, consider the very common case of a proportional plus integral (PI) controller, which is essentially the same task as that being addressed here; the proportional component corresponds to PFR and the integral component corresponds roughly to NEM AGC regulation. In a PI controller the proportional part is the first line of response while the integral part removes any offset over time. There is no question that, to avoid "double counting" the proportional part of the control should cut out at some arbitrary time when the integral component takes over. Both operate together to control whatever error needs correction. The AEMC seems to argue that regulation and primary frequency control are at least partial substitutes. They are not. Control theory and practice requires both to work together for best results.

We also note that FCAS providers are paid not only for providing this service but also in the energy market. This has never been a cause for concern by rule makers and regulators.

2.4 Distinguishing Provision and Cause

Regulation Causer Pays focuses on measuring the causers of frequency deviations as a mechanism to pay for the enablement of regulation: it is "single sided". For PFR Causer Pays, there is no enablement market proposed, as PFR is mandated. Instead, we propose to identify the provision of the PFR service and remunerate this from charges levied on cause: the approach is "double sided". The rate of charging and payment will be determined by the approach outlined in sub-section 2.8. We distinguish provision and cause in the following way.

- If ACE-REG is positive (need more injection) and if the MW deviation of a unit is positive (injecting more than scheduled in the energy market), the unit is a **provider of raise PFR** at the time.
- If ACE-REG is positive (need more injection) and if the MW deviation of a unit is negative (injecting less than scheduled in the energy market), the unit is a **causer of raise PFR** at the time.

[4] *Frequency Control Frameworks Review Final Report*: AEMC 26 July 2018 – p 100.

- If ACE-REG is negative (need less injection) and if the MW deviation of a unit is negative (injecting less than scheduled in the energy market), the unit is a **provider of lower PFR** at the time.
- If ACE-REG is negative (need less injection) and if the MW deviation of a unit is positive (injecting more than scheduled in the energy market), the unit is a **causer of lower PFR** at the time.

These different situations can be summarised in the following simple table.

Table 1: Raise and Lower PFR; Provision and Cause

	MW deviation > 0	**MW Deviation < 0**
ACE-REG > 0	Raise PFR provision	Raise PFR cause
ACE-REG < 0	Lower PFR cause	Lower PFR provision

Note that a unit can be a provider or a causer at different times (reflective of the technical characteristics of the PFR provider) within the same 5-minute dispatch interval. A high-performance provider can sometimes be a causer, although provision will tend to dominate its net outcome over a 5-minute dispatch interval as well as over a much longer settlement period.

2.5 Dealing with Unmetered Energy

In the NEM, only scheduled and semi-scheduled units are metered at the 4-second level by the AGC. Most load is not metered at this level. However, if we include losses as part of loads and ignore regional distinctions for the moment, electrical energy balance demands that the unmetered load equal the net metered generation, with an opposite sign, so that net power (and energy) sums to zero. Dynamic mismatch between load and generation drives frequency change, which is slowed by system inertia while being countered by generator frequency response and by a residual of load relief to restore the balance and thus stabilise frequency. This logic applies at the 5-minute as well as the 4 second level.

It is possible to break down this residual into two components; that due to AEMO's forecast error of the unscheduled market elements, and that due to helpful load changes as frequency changes, as measure by AEMO's Area Control Error (ACE). Equations 13.2 and 13.3 in the Appendix A set out these options.

We can allocate causer costs to unmetered parties according to this residual measure. We would have no regional disaggregation but this could be partially recovered after the event by allocating costs pro-rated by energy, as with Regulation Causer Pays. The way this further allocation of residual costs (or payments) could be handled is beyond the scope of this project.

2.6 Performance Measure and Cost Allocation

Given the above distinctions, the measure of performance in any 4-second interval is given by

Performance_Factor = ACE-REG x MW_Deviation

This measure makes intuitive sense because the larger the requirement and the larger the provision or cause, the larger is the measure. However, its validity is by no means obvious. Many other measures with similar intuitive properties could be devised. However, the measure is consistent with the outcome of a more theoretical analysis based on control theory, where the objective is to minimise the variance of the frequency deviation over time. Such a detailed justification is beyond the scope of the current project[5], where the scope as deliberately limited to rely on existing assumptions the Causer Pays approach.

In an earlier project commissioned by CS Energy[6], we have implemented a calculation procedure for estimating each 5 minutes the cost of provision by units of raise and lower services. With such a measure available we can proceed as follows. Raise and lower PFR are treated independently and similarly, so we discuss raise PFR only:

- In each 5 minutes, allocate the estimated cost of provision to the providers, in proportion to their accumulated provision factors.
- Using the same apportioning factor, allocate a charge to the cause provision measured within that 5-minutes

2.7 Accumulating 5-Minute Factors

As with Regulation Causer Pays, it is convenient to accumulate performance factors measured each 4 seconds into 5-minute aggregate factors for later settlement, analysis and presentation. Our system will need to track performance in four categories (Raise and Lower, Provision and Cause) for each SCADA metered unit, as well as the residual.

The payment calculation described above (and in more detail in the Appendix) can then be done on these 5-minute values at settlement time. Further, the workings of the system can be more conveniently analysed over long periods with 5-minute values.

2.8 Summary of PFR Double Sided Causer Pays Procedure

Part of the calculation process is set out below as an example, considering only the Raise costs and payments for PFR for a particular unit ($\mathbf{i}$). The process will be similar for PFR Lower.

Given:

4sec factors (deviation × ACE-REG) ($\boldsymbol{F_{4s}}$)

5min estimate of efficient cost of Raise (***RaiseCost***)

Provider	Causer
$ProviderFactor_i = \sum F_{4s} \text{ if } \mathrm{F}_{4s} > 0$	$CauserFactor_i = \sum -F_{4s} \text{ if } \mathrm{F}_{4s} < 0$

[5] The linear-quadratic control problem is an elementary starting point for such an analysis. See https://en.wikipedia.org/wiki/Linear%E2%80%93quadratic_regulator.

[6] *Costing of Primary Frequency Control: Report to CS Energy* -6 August 2019. Available on request from IES.

Provider	Causer
$Payment_i(for\ unit\ i) = \frac{ProviderFactor_i}{\sum_{All\ units} ProviderFactor_i} \times RaiseCost$	$Cost_i(for\ unit\ i) = \frac{CauserFactor_i}{\sum_{All\ units} ProviderFactor_i} \times RaiseCost$
There will be a non-zero residual component to be allocated to the non-metered parties in the system (could be positive or negative, i.e. it could be paid to or recovered from the non-metered parties)	

3 Implementation

3.1 Data Requirements

The following are required to test and implement the PFR Causer Pays mechanism:

- 4-second generation/consumption of each unit
- 5-minute dispatch targets of each unit
- 4-second frequency deviation (ACE-REG is a function of frequency deviation)
- 5-minute regional prices and regional generation profiles
- Various static parameters that inform the cost formula such as marginal costs, throttle ratio etc

Apart from the 4-second generation/consumption data, this is the same data set used in the PFR cost calculation. Note that most non-scheduled participants have no centralised 4-second metering (SCADA).

The data is published by AEMO either in its dispatch data (published every 5 minutes) or in its causer pays data (published every day). IES maintains a replicated database(s) that reads in the published data and stores it locally.

3.2 Processing

Processing of raw data for the purpose of this project proceeds in stages.

- Market data and 4 second data are downloaded from AEMO.
- The 4 second data are processed into 5-minute accumulated values each day, after download from AEMO.
- The 5-minute data are accessed as required for project reporting. 4-second reports have also been developed for verifying 5-minute calculations and for internal use. Selected high level reports will be made available for public viewing.

IES maintains a dedicated server for the database and will in time move the processing to a dedicated server as well.

3.3 Reporting

3.3.1 Overview

Reporting has been implemented online in NEO-Point as a set of charts in most cases. Some numerical data is also provided. Subsets of these reports can be published to specific parties as required. There are two main types.

- 4-Second Charts

  These charts are mainly intended to illustrate the calculation process and its outcome. The duration shown is typically 5 minutes or a few dispatch intervals. The results of these calculations are accumulated into 5-minute values, separated into raise and lower PFR and in any cases split into provider and causer

- 5-Minute Charts

  These charts summarise the outcome of the process and are intended to be run over a settlement period or any other period of interest.

The Appendix to this report describes these charts in more detail with associated screenshots. Following is a very brief description of the purpose of each set. Generally, each set may contain charts for raise and lower, provider and causer and combinations in various ways.

3.3.2 Individual Allocations

The charts in this set display the cost allocations from the PFR Causer Pays process to a selected unit over a selected period.

3.3.3 All Allocations

The charts in this set display the distribution of funds from the PFR Causer Pays process across the system for a selected period, showing both causers (payers) and providers (who get paid).

3.3.4 All Allocations (Normalised)

The charts in this set display similar data to that of the previous section; the difference is that the allocations are normalised by dividing by measured output. This adjustment better illustrates the relative performance of a unit, independent of its size.

3.3.5 K-Factors and Deviation Pricing

The charts in this set display price profiles which, when applied to generator load profiles, give the same outcome as PFR causer pays allocation. In this project they are termed K-Factors and the corresponding prices are termed K-Prices. These prices are similar to one component of a deviation price, which would be a more complete system for dealing with frequency deviations.

3.3.6 Intermediate Steps

The charts in this set show the calculation of the PFR causer pays factors step by step for a selected plant. These charts can be used to verify the calculations as well as identify the reason for a particular trend/result.

3.3.7 Intermediate Cost Steps

The charts in this set show the calculation of the efficient cost estimate step by step. Note that this work was completed as part of previous work commissioned by CS Energy. More information can be found from documentation supplied as part of previous work as well as several earlier and related projects over a period of several years.

Appendix A

Project on Double-sided Causer Pays for Primary Frequency Response

Formulation and Presentation Documentation

Project on Double-sided Causer Pays for Primary Frequency Response

Formulation and Presentation Documentation

1 Project Brief

IES has been contracted by CS Energy to demonstrate with calculations and charting how a two-sided market for Primary Frequency Response (PFR) could work. This document outlines the calculations proposed to be performed together with supporting live charts.

2 Information Available

1. AEMC PFR consultation paper and related prior reports
2. Previous PFR Costing work by IES for CS Energy dated August,2019
3. Previous Market Improvement Report by IES for CS Energy dated April 2017
4. Day after 4 second regulation data from AEMO
5. 5-minute market data from AEMO.

3 Broad Approach

The data necessary to do these calculations are available a day after real time. Real time calculations would require real time frequency deviation measurements (which we can do) as well as scheduled unit deviations, which we cannot easily do (although we note it could be estimated for an individual company using their 4 second SCADA data).

We propose to calculate a set of 5-minute values for each day after the 4 second datasets are made available by AEMO. Over time, this will allow information over multiple settlement periods to be recorded.

We will utilise calculations for an estimated “Efficient Cost” of PFR raise and lower in each dispatch interval which was developed during a previous project for CS Energy. The purpose is to distribute this Efficient Cost between participants. Please note it is not necessary to use this Efficient Cost estimate; any other 5-minute cost function may be used.

It is important to recognise that performance measure will reflect the current lack of incentives for PFR provision. If a mandate, compensation mechanism or incentive were to be introduced, the performance of units would change, sometimes dramatically. The allocation of costs to certain units under the current operating regime is not a reliable indicator of their future allocation, as units may change operating regime in response to the incentive. This is the aim in implementing the incentive.

4 Calculations

4.1 Data

4.1.1 Given Values

#	Variable Name	Description	Data Frequency
1	Gen_t^u	Measured output for a unit (*with duid = u*) at time t[1]	4sec
2	$GenReg_t^u$	The AGC (nudging) signal sent to unit(u) at time t	4sec
3	$GenDispatch_t^u$	Dispatch targets of unit (u) for Dispatch interval (DI) ending at (t)	5min
4	$OppCost_t$	Opportunity cost for DI ending at (t), using the price from the region with max reserve	5min
5	$HzDev_t$	Frequency deviation at time t	4sec

4.1.2 Computed Values

#	Variable Name	Description	Data Frequency
6	$AceReg_t$	The system requirement (area control error)	4sec
7	$NAceMin_t, NAceAvg_t$ $PAceMax_t, PAceAvg_t$	Grouped Ace Values	5min
8	$HeadroomCP_t, FootroomCP_t,$ $HeadroomUP_t, FootroomUP_t,$	Respective Prices for each DI	5min

[1] Though not explicitly mentioned, the signs of these quantities have to be consistent with the idea that a larger quantity is INCREASING MW into the system. The signs of some units (loads, batteries) will need to be inverted to reflect this.

#	Variable Name	Description	Data Frequency
9	$HeadroomCC_t, FootroomCC_t,$ $HeadroomUC_t, FootroomUC,$	Respective costs for each DI	5min
10	$RaiseCost_t, LowerCost_t$	Cost of Raise and Lower for each DI	5min
11	$LinearGenDispatch_t^u$	Linear interpolated dispatch trajectory for unit(u) at time (t)	4sec
12	$Trajectory_t^u$	Expected trajectory of unit (u) at time (t)	4sec
13	$Deviation_t^u$ $/Deviation_t^{unmetered}$	Deviation from trajectory of unit(u)/unmetered participants at time (t)	4sec
14	$Factor_t^u$	Factor of a unit(u) (or unmetered) at time (t)	4sec
15	$PRFactor_t^u$	Provider factor for unit(u) (or unmetered) at time (t) for Raise service	5min
16	$CRFactor_t^u$	Causer factor for unit(u) (or unmetered) at time (t) for Raise service	5min
17	$PLFactor_t^u$	Provider factor for unit(u) (or unmetered) at time (t) for Lower service	5min
18	$CLFactor_t^u$	Provider factor for unit(i) (or unmetered) at time (t) for Lower service	5min
19	$KRFactor_t$	K-factor at time (t)	5min
20	$KLFactor_t$	K-factor at time (t)	5min

#	Variable Name	Description	Data Frequency
21	$PRCost_t^u, CRCost_t^u$ $PLCost_t^u, CLCost_t^u$	Respective costs/payments to unit(i) (or unmetered) for DI(t)	5min

Refer to the respective equations for their calculations.

4.2 Equations

6. Eq 6

ACE-REG is the MW requirement of the system as a result of frequency deviation, given by

$$AceReg_t = -G_{ace} \times HzDev_t$$

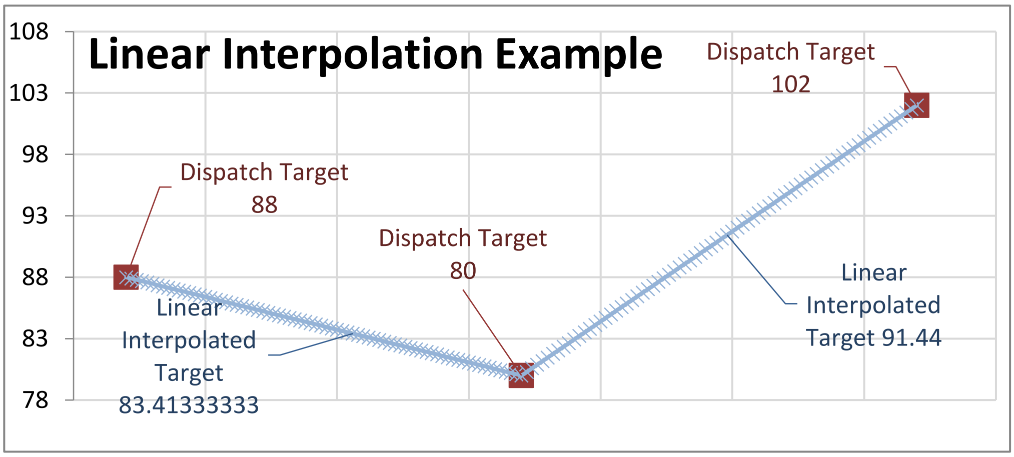
In qualitative terms it can be thought of as the additional power required to maintain a stable system. If ACE-REG is negative: the system requires more energy usage; if the ACE-REG is positive: the system requires more energy production.

At the time of writing AEMO uses 2800 for the G_{ace} parameter in its AGC systems. If needed this parameter can be modified at a later time.

Note: This formulation of ACE-REG does not account for time error as AEMO's formulation would. Accounting for time error on the PFC timescale may not be appropriate in any case, but this can be kept under review.

7. Eq 11

A linear interpolation is performed between each dispatch target ($GenDispatch_t^u$) and sampled at every 4sec interval to obtain $LinearGenDispatch_t^u$. This process is also done in Regulation causer pays.



8. Eq 12

We considered 3 different methods to compute the trajectory. "Normal" is the preferred option, but results will be generated for all methods.

Normal	$Trajectory_t^u = LinearGenDispatch_t^u$
AGC	$Trajectory_t^u = LinearGenDispatch_t^u + GenReg_t^u$
Filter	$Trajectory_t^u = Filter(Gen_t^u, TC)$ Note: TC is a time constant representing the time delay characteristic of the AGC system (currently considering 35sec), it can be a configurable parameter.

The results for these methods can be displayed from the NEOpoint platform.

9. Eq 13.1

$$Deviation_t^u = Gen_t^u - Trajectory_t^u, \qquad \forall\, u \in units$$

Treatment of unmetered or residual elements of the system

The following two equations, 13.2 and 13.3 highlight two different approaches to calculating a 'deviation' for the elements of the power system that are not measured using the central SCADA system.

The two approaches arise from different premises:

1. The sum of all deviations is zero. The net of all measured deviations equals the unmeasured deviation; or
2. The sum of all deviations is ACE. The difference between ACE and the net of all measured deviations equals the unmeasured deviation.

It is also linked to the amount of proportional governor response freely available in the system. There is circularity between what is being incentivised (correction of frequency error through primary governor control) and the size of the error for a given change in frequency. As will be explained, the aim of this project is to measure the response of units and pay them for it. We assume that this is presently accounted for in the SCADA measurements, and ACE is solely attributed to load relief. This assumption may be reviewed with the implementation of mandatory primary frequency control from October 2020.

For these reasons, 13.2 is presently the preferred approach.

10. Eq 13.2

This formulation would result in a residual deviation. This residual can be directly calculated as:

$$Deviation_t^{unmetered} = -\sum^{u \in units} Deviation_t^u$$

A useful property of this is that the sum of all deviations is 0. An alternative formulation breaks the left hand side of 13.2 into 2 parts; that due to unscheduled forecast error and that due to unscheduled load relief. Note that the quantum of load relief is measured by ACE. ACE is the estimated MW deviation given by:

$$Ace_t = G_{ace} \times HzDev_t$$

It is the negative of ACE-REG.

11. Eq 13.3

$$Forecast\_Error_t^{unmetered} - Ace_{t=} = -\sum^{u \in units} Deviation_t^u$$

One could settle the unmetered component based on the forecast error, on the load relief it provides or the net of the two which is the left-hand side of both 13.2 and 13.3. Advantages of settling on the net of the two is that it would make reasonable commercial sense and the system would balance without additional pro-rating.

Equations 13.2 and 13.3 are both implemented and results using both implementations can be viewed on NEOpoint by selecting the 'resnorm' (13.2) or the 'resace' (13.3) methods. From this point, the unmetered is considered a first-class participant; all equations defined for a participant with a duid is also defined for the unmetered participants (as a group).

12. Eq 14

A factor that indicates a unit's relative performance can be calculated as the product of ACE-REG and its deviation:

$$Factor_t^u = AceReg_t \times Deviation_t^u, \qquad \forall\, u\ \in \{units, unmetered\}$$

This is similar to the formulation used to calculate regulation causer pays factors. The benefits are listed below:

This formulation makes it obvious if a deviation is good (provider) for the system or bad (causer). For example, if the system required more energy production (ACE-REG > 0) and the unit produced more than expected (Deviation > 0); this unit should be rewarded. The same should happen when the system needs more energy usage (ACE-REG < 0) and the unit produced less than expected (Deviation < 0). This unit should be penalised for the other 2 situations: (ACE-REG < 0, Deviation > 0) and (ACE-REG > 0, Deviation < 0).

The formulation also represents the benefit of responding when ACE-REG has high deviation. In this situation, the system is getting more unstable and units that provide frequency control should be rewarded more than if they had provided during a low deviation.

Finally, the formulation also scales factors based on unit's response. i.e. a unit with a more positive factor is a unit that provids a better response when the system needs it.

13. Eq 15

$PRFactor_t^i$ is the factor that represents its provider (P) share to the raise (R) service; in words it can be said is the sum of all positive factors when the system requires raise OR:

$$PRFactor_t^u = \sum^{t' \in DI(t)} Factor_{t'}^u \ where\ [Factor_{t'}^u \geq 0\ and\ AceReg_{t'} > 0]$$

Where $DI(t)$ is the set of 4sec time points that belong to the dispatch interval ending at t.

Eq 16, 17, 18 are similar to this. The following matrix denotes options for P, provider and C, causer.

		$AceReg_{t'}$	
		>0 (positive)	<0 (negative)
$Factor_{t'}^u$	>0	$PRFactor_t^u$	$PLFactor_t^u$
	<0	$CRFactor_t^u$	$CLFactor_t^u$

14. Eq 16

Note: Causer factors are negative by design

$$CRFactor_t^u = \sum^{t' \in DI(t)} Factor_{t'}^u \ where\ [Factor_{t'}^u < 0\ and\ AceReg_{t'} > 0]$$

15. Eq 17

$$PLFactor_t^u = \sum^{t' \in DI(t)} Factor_{t'}^u \ where\ [Factor_{t'}^u \geq 0\ and\ AceReg_{t'} < 0]$$

16. Eq 18

$$CLFactor_t^u = \sum^{t' \in DI(t)} Factor_{t'}^u \ where\ [Factor_{t'}^u < 0\ and\ AceReg_{t'} < 0]$$

17. Eq 19

K-Factor is defined as the cost divided by sum of provider factors

$$KRFactor_t = \frac{RaiseCost_t}{\sum^{u \in \{units, unmetered\}} PRFactor_t^u}$$

18. Eq 20

Similar to Eq 19

$$KLFactor_t = \frac{LowerCost_t}{\sum^{u \in \{units,unmetered\}} PLFactor_t^u}$$

19. Eq 21

The final allocation of cost to a particular unit is calculated by apportioning the cost of the service based on the calculated factors. The apportioning is done such that the amount collected from the causers is enough to cover the amount distributed to the providers.

$$PRCost_t^u = \frac{PRFactor_t^u}{\sum^{i \in \{units,unmetered\}} PRFactor_t^u} \times RaiseCost_t$$

$$CRCost_t^u = -\frac{CRFactor_t^u}{\sum^{i \in \{units,unmetered\}} CRFactor_t^u} \times RaiseCost_t$$

$$PLCost_t^u = \frac{PLFactor_t^u}{\sum^{i \in \{units,unmetered\}} PLFactor_t^u} \times LowerCost_t$$

$$CLCost_t^u = -\frac{CLFactor_t^u}{\sum^{i \in \{units,unmetered\}} CLFactor_t^u} \times LowerCost_t$$

K-Factor Significance

Under the resnorm method (Using Eq 13.2 for calculating the unmetered deviation). It can be noted that

$$\sum^{u \in \{units,unmetered\}} Deviation_t^u = 0$$

Which leads to

$$\sum^{u \in \{units,unmetered\}} Factor_t^u = 0$$

Consider a 5min interval, and only those 4sec periods where ACE-REG > 0 (Raise is required)

$$\sum^{t' \in DI(t), u \in \{units,unmetered\}} Factor_{t'}^u \ where\ [AceReg_{t'} > 0] = 0$$

$$\sum^{t' \in DI(t), u \in \{units,unmetered\}} Factor_{t'}^u \ where\ \left[Factor_{t'}^u \geq 0 \ and\ AceReg_{t'} > 0\right]$$

$$+ \sum^{t' \in DI(t), u \in \{units,unmetered\}} Factor_{t'}^u \ where\ \left[Factor_{t'}^u < 0 \ and\ AceReg_{t'} > 0\right] = 0$$

$$\sum^{u \in \{units,unmetered\}} PRFactor_t^u + \sum^{u \in \{units,unmetered\}} CRFactor_t^u = 0$$

Similarly, for Lower

$$\sum^{u \in \{units, unmetered\}} PLFactor_t^u + \sum^{u \in \{units, unmetered\}} CLFactor_t^u = 0$$

Eq 21 can be rewritten as

$$PRCost_t^u = \frac{PRFactor_t^u}{\sum^{i \in \{units, unmetered\}} PRFactor_t^u} \times RaiseCost_t$$

$$CRCost_t^u = \frac{CRFactor_t^u}{\sum^{i \in \{units, unmetered\}} PRFactor_t^u} \times RaiseCost_t$$

$$PLCost_t^u = \frac{PLFactor_t^u}{\sum^{i \in \{units, unmetered\}} PLFactor_t^u} \times LowerCost_t$$

$$CLCost_t^u = \frac{CLFactor_t^u}{\sum^{i \in \{units, unmetered\}} PLFactor_t^u} \times LowerCost_t$$

In other words

$$PRCost_t^u = PRFactor_t^u \times KRFactor_t$$

$$CRCost_t^u = CRFactor_t^u \times KRFactor_t$$

$$PLCost_t^u = PLFactor_t^u \times KLFactor_t$$

$$CLCost_t^u = CLFactor_t^u \times KLFactor_t$$

Note this will only hold for the 'resnorm' method.

4.3 Methods

As previously stated, in the course of research several methods were considered for calculating the double-sided causer pays factors. No calculation process is removed/deleted but might be superseded by a newer (more accurate) method. An overview of each method is provided below. They are a selectable parameter in the NEOpoint charts (under the "904 Double-Sided Causer Pays (COMPLETE)" favourite), allowing the viewer to compare different methods' results.

Normal*	This is the base method where expected trajectory is equal to the linear dispatch trajectory (See Eq 12)
AGC*	The expected trajectory is set to the sum of the linear dispatch trajectory and the AGC Reg signal (See Eq 12)
Filter*	The expected trajectory is set to the filtered measured output (See Eq 12)
Resnorm	This is similar to the "Normal" method except that the unmetered are first class participants and their deviations are calculated using Eq 13.2
Resace	This is similar to the "Normal" method except that the unmetered are first class participants and their deviations are calculated using Eq 13.3

*In these methods, special provisions are not made for the unmetered participants and their deviations/factors are not recorded.

Note: Not all users of NEpoint would want to switch between the different methods. Therefore, another set of reports (”905 Double-Sided Causer Pays” favourite) are provided which fixes the method. At the moment the method used for these fixed reports is the “resnorm” method; this can be easily changed to another method if required.

5 Charting and Other Presentations

The results are displayed in the form of charts available through the NEOpoint platform. Results are organised into groups, an overview of each group and the charts that constitute each group is provided in the next section. Sample screenshots of each chart is provided in the Appendix.

5.1 Individual Allocations

These charts display the costs that are allocated to a particular unit.

01 Separate Allocations (raise)	Displays the 5min causer and provider allocations for the raise service
02 Separate Allocations (lower)	Displays the 5min causer and provider allocations for the lower service
03 Allocations (raise)	Displays sum of causer and provider allocations (for each 5min period) for the raise service
04 Allocations (lower)	Displays sum of causer and provider allocations (for each 5min period) for the lower service
05 Allocations (provider)	Displays sum of provider allocations (for each 5min period) for both services
06 Allocations (causer)	Displays sum of causer allocations (for each 5min period) for both services
07 Allocations (total)	Displays sum of all allocations (for each 5min period)
08 All Plant Allocations	Displays sum of all allocations (over the selected period); with separate entries for each of the 4 allocations.
09 Separate Allocations	Displays all 4 allocation groups over a selected period

5.2 All Allocations

Compares the allocations for all units considered in the calculation.

01 Total Raise High-end	Displays a bar chart comparing the top paid/paying plants (for the raise service)

02 Total Lower High-end	Displays a bar chart comparing the top paid/paying plants (for the lower service)
03 Total Raise Low-end	Displays a bar chart comparing the bottom paid/paying plants (for the raise service)
04 Total Lower Low-end	Displays a bar chart comparing the bottom paid/paying plants (for the lower service)
05 Total All Plants	Displays a table of all allocations for both services and for all plants (ordered by total allocation)
06 Total Net High-end	Displays a bar chart comparing the top paid/paying plants (for both raise and lower)
07 Total Net Low-end	Displays a bar chart comparing the bottom paid/paying plants (for both raise and lower)

5.3 All Allocations (Normalised)

Similar to charts in the previous section but the allocations are normalised by measured output. This gives a better representation of the allocations by taking into account the size of the unit.

01 Total Raise High end (Norm)	Displays a bar chart comparing the top normalised paid/paying plants (for the raise service)
02 Total Lower High end (Norm)	Displays a bar chart comparing the top normalised paid/paying plants (for the lower service)
03 Total Raise Low end (Norm)	Displays a bar chart comparing the bottom normalised paid/paying plants (for the raise service)
04 Total Lower Low end (Norm)	Displays a bar chart comparing the bottom normalised paid/paying plants (for the lower service)
05 Total Raise High end Comparison (Norm)	Displays the normalised costs but in the same order as the “01 Total Raise High” chart in Section “5.2 All Allocations”
06 Total Lower High end Comparison (Norm)	Displays the normalised costs but in the same order as the “02 Total Lower High” chart in Section “5.2 All Allocations”
07 Total Raise Low end Comparison (Norm)	Displays the normalised costs but in the same order as the “03 Total Raise Low” chart in Section “5.2 All Allocations”
08 Total Lower Low end Comparison (Norm)	Displays the normalised costs but in the same order as the “04 Total Lower Low” chart in Section “5.2 All Allocations”
09 Total All Plants (Norm)	Displays a table of all normalised allocations for both services and for all plants (ordered by total allocation)

5.4 K Factors

The charts in this section display information regarding the K-Factors. The K-Price is displayed in these charts; the K-price is essentially the price of deviation. It can be found from the cost formula. Consider $PRCost_t^u$

$$PRCost_t^u = PRFactor_t^u \times KRFactor_t$$

$$PRCost_t^u = \left(\sum^{t' \in DI(t)} AceReg_t \times Deviation_t^u \; Where \; [..] \right) \times KRFactor_t$$

$$PRCost_t^u = \left(\sum^{t' \in DI(t)} AceReg_t \times KRFactor_t \times Deviation_t^u \; Where \; [..] \right)$$

$$PRCost_t^u = \left(\sum^{t' \in DI(t)} KRPrice_t \times Deviation_t^u \; Where \; [AceReg_t \geq 0 \; and \; Factor_t^u \geq 0] \right)$$

Similarly

$$CRCost_t^u = \left(\sum^{t' \in DI(t)} KRPrice_t \times Deviation_t^u \; Where \; [AceReg_t \geq 0 \; and \; Factor_t^u < 0] \right)$$

$$PLCost_t^u = \left(\sum^{t' \in DI(t)} KLPrice_t \times Deviation_t^u \; Where \; [AceReg_t < 0 \; and \; Factor_t^u \geq 0] \right)$$

$$CLCost_t^u = \left(\sum^{t' \in DI(t)} KLPrice_t \times Deviation_t^u \; Where \; [AceReg_t < 0 \; and \; Factor_t^u > 0] \right)$$

Hence

$$KPrice = \begin{cases} AceReg_t \times KRFactor_t, & AceReg_t \geq 0 \\ AceReg_t \times KLFactor_t, & AceReg_t < 0 \end{cases}$$

The KPrice can be thought of as another way to digest the information returned by the double-sided causer pays method. It is effectively a system-wide price on a unit's deviation.

01 K Factor calc (lower)	Displays the constituents of KLFactor (sum of PLFactor and Lower Cost)
02 K Factor calc (raise)	Displays the constituents of KRFactor (sum of PRFactor and Lower Cost)
03 K Factors	Displays the KRFactor and KLFactor
04 K Factors (with ACE-REG)	Displays the KFactors and ACE-REG; can be used to verify KPrice calculation

05 K Price	Displays KPrice as well as wholesale energy price, opportunity cost used to calculate the raise/lower cost
06 K Price (with ACE, OppC)	Displays KPrice with ACE and opportunity costs

5.5 Intermediate Steps

The aim of the charts in this section is to show the calculation of the factors step by step for a selected plant.

01 Trajectory	Displays 4sec measured output and the expected trajectory
02 Deviations	Displays deviations from the trajectory and the system ACE-REG
021 Deviations Coloured	Displays the same information as above but colours the deviations and ACE-REG differently depending whether it is positive or negative (This is useful in identifying positive or negative factors in the next chart)
03 Factors	Displays the factors of the selected unit
04 Factors	Displays the cumulative 4sec factors of the selected unit
05 Factors (lower)	Displays the 5min lower factors as well as the 4sec factors during the times when lower was required (ACE-REG < 0)
06 Factors (raise)	Displays the 5min raise factors as well as the 4sec factors during the times when raise was required (ACE-REG < 0)
07 Factors (lower, cumulative)	Displays the 5min lower factors as well as the cumulative 4sec factors during the times when lower was required (ACE-REG < 0)
08 Factors (raise, cumulative)	Displays the 5min raise factors as well as the cumulative 4sec factors during the times when raise was required (ACE-REG < 0)

5.6 Intermediate Cost Steps

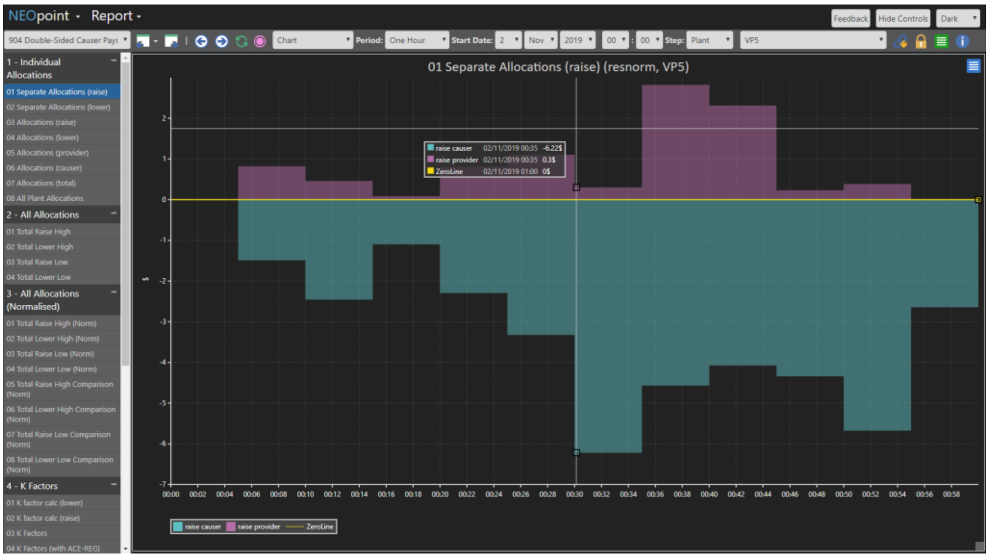
The aim of the charts in this section is to show the calculation of the raise and lower pfc service step by step. See previous work for formula and explanation.

01 Opportunity Cost	Displays the 5min opportunity costs for PFR
02 Grouped ACE	Displays the 4 grouped values of ACE
03 Capacity/Utilisation Prices	Displays the Capacity and Utilisation prices for providing footroom or headroom
04 Capacity/Utilisation Costs	Displays the Capacity and Utilisation costs for providing footroom or headroom
05 Total Costs	Displays the total raise or lower PFR costs

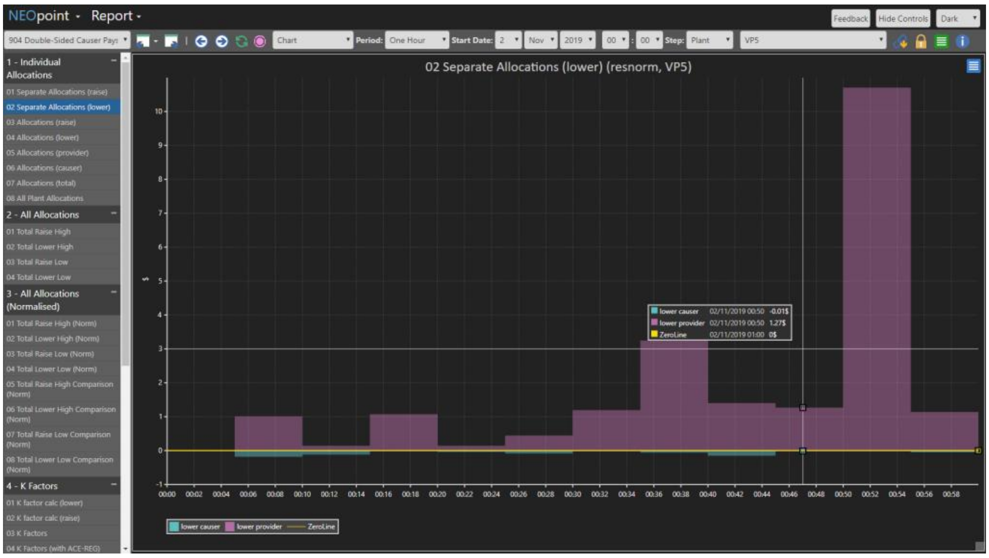
6 Appendix A – Chart Screenshots

6.1 Individual Allocations

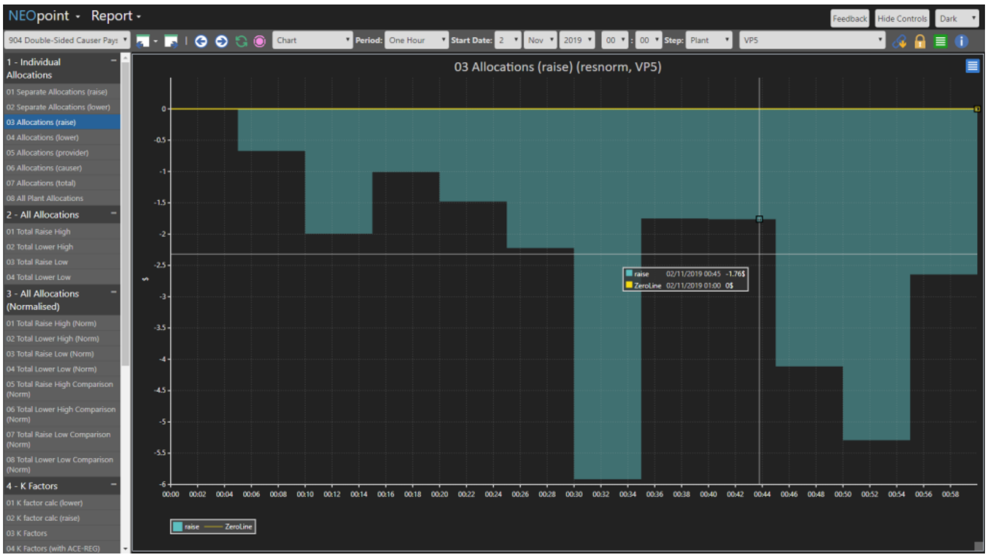
01 Separate Allocations (raise)



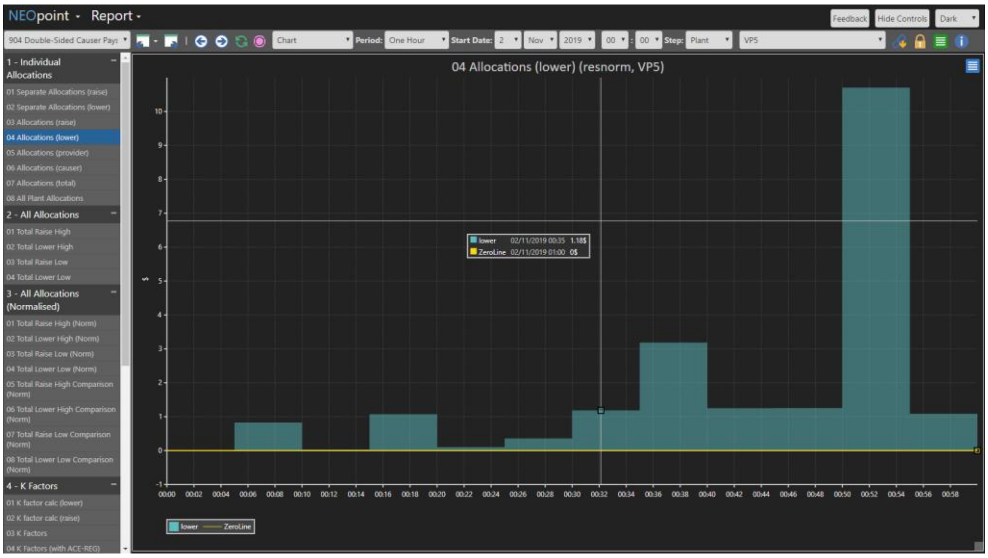
02 Separate Allocations (lower)



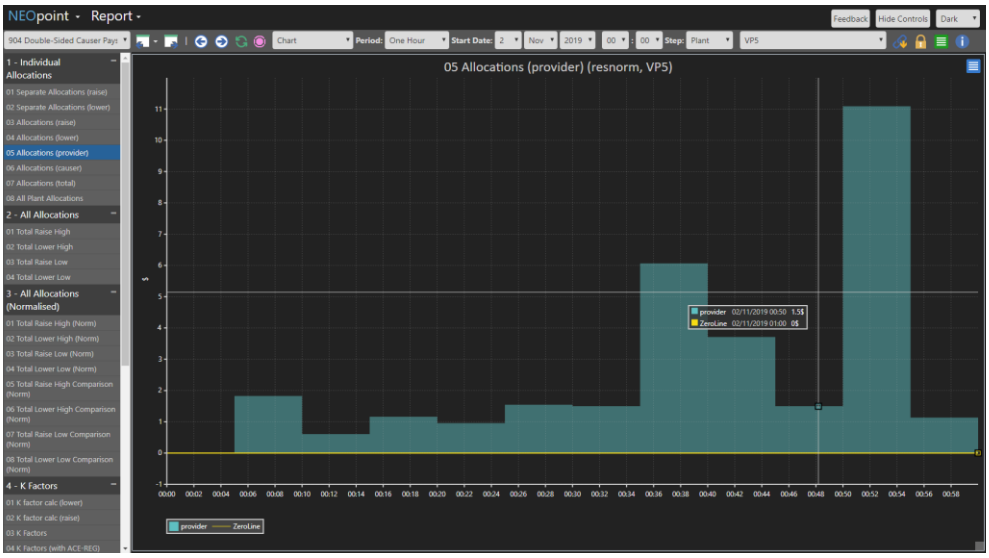
03 Allocations (raise)



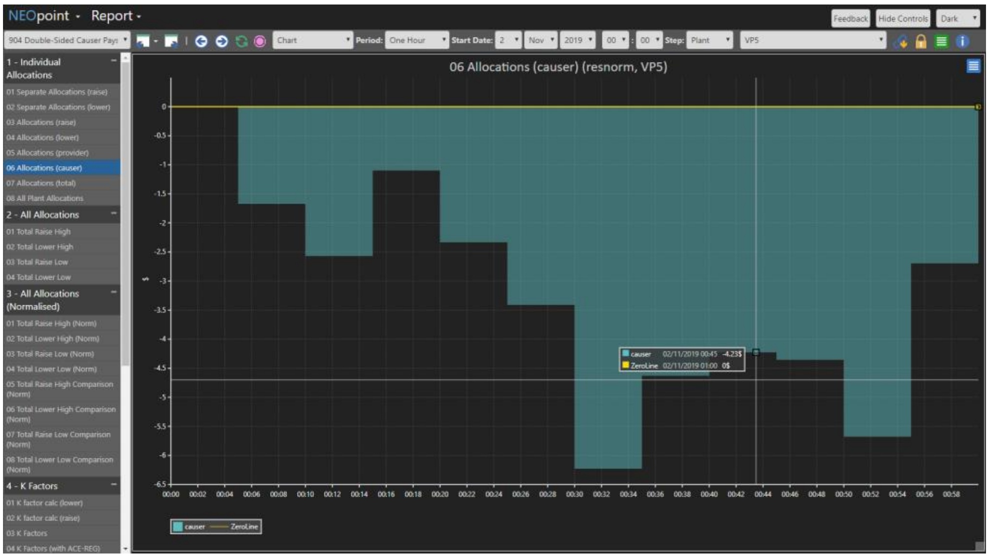
04 Allocations (lower)



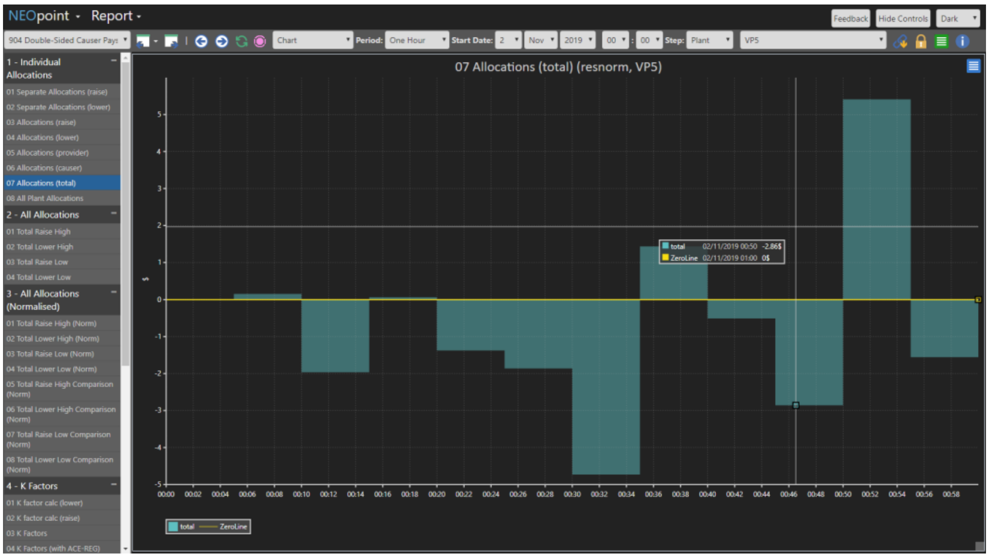
05 Allocations (provider)



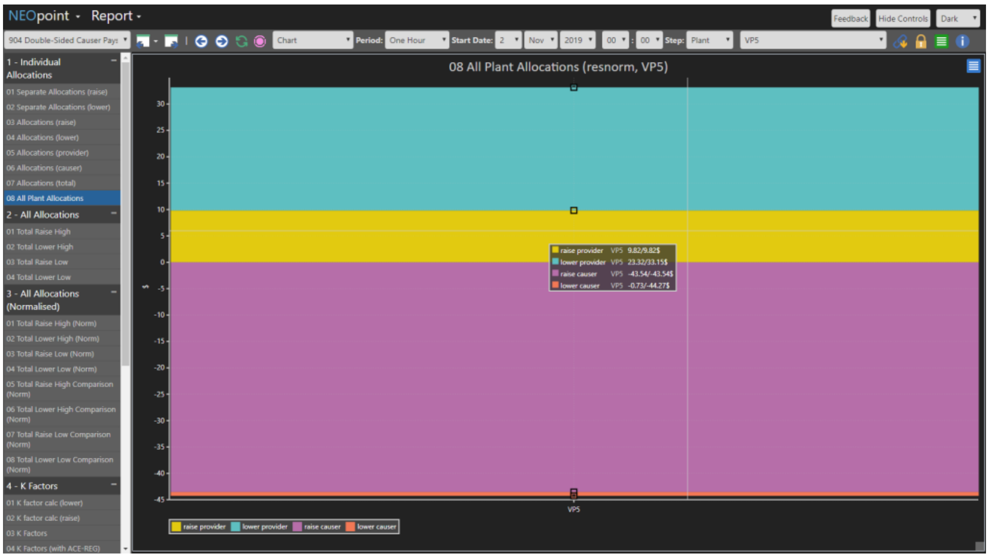
06 Allocations (causer)



07 Allocations (total)

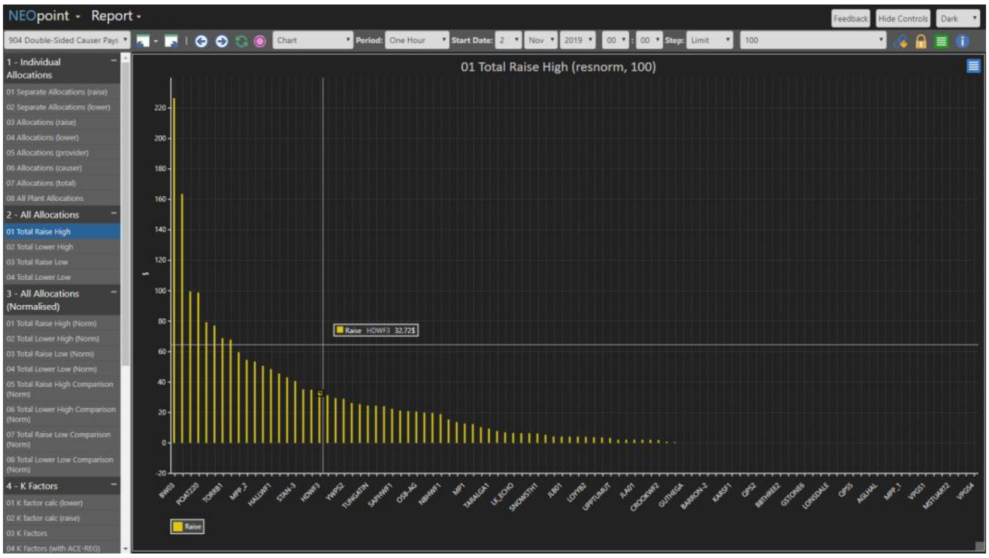


08 All Plant Allocations

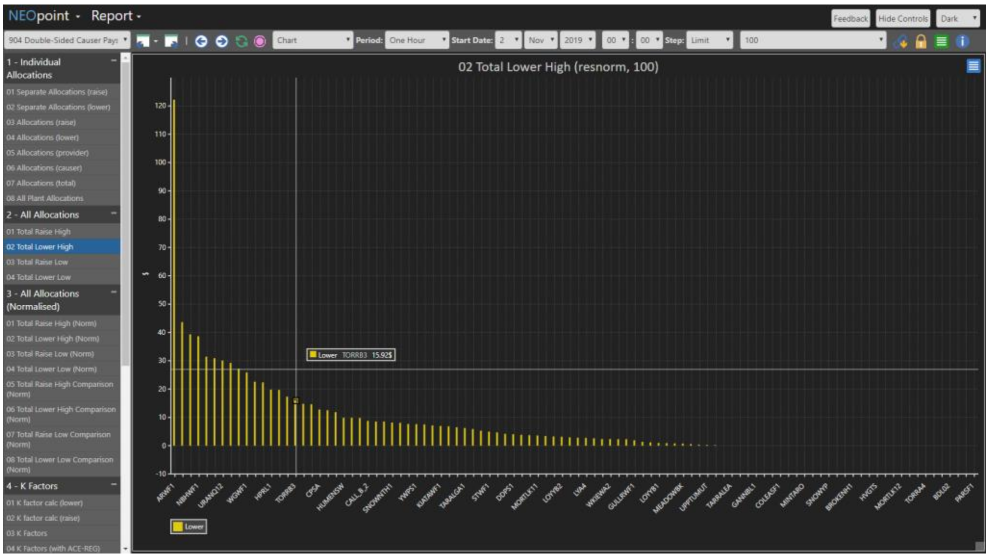


6.2 All Allocations

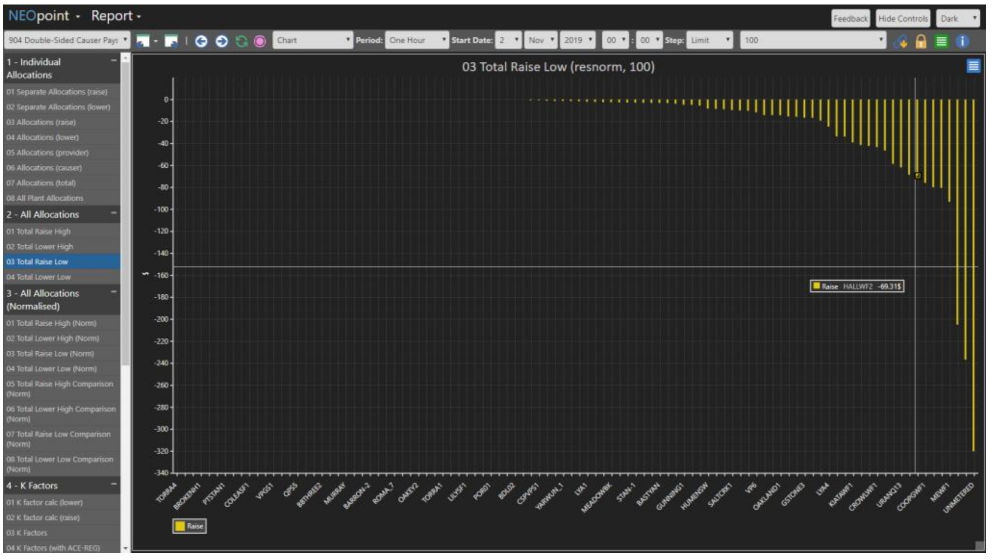
01 Total Raise High



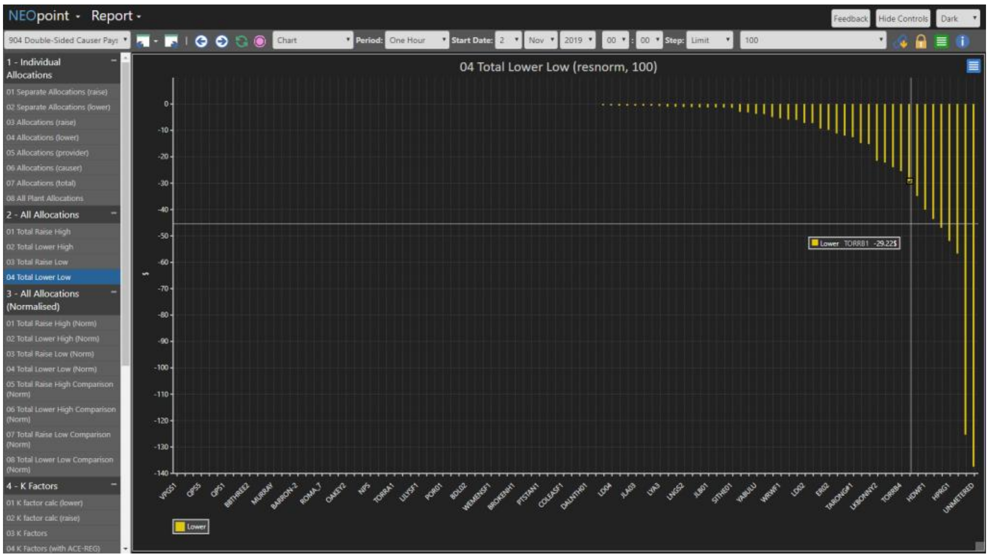
02 Total Lower High



03 Total Raise Low

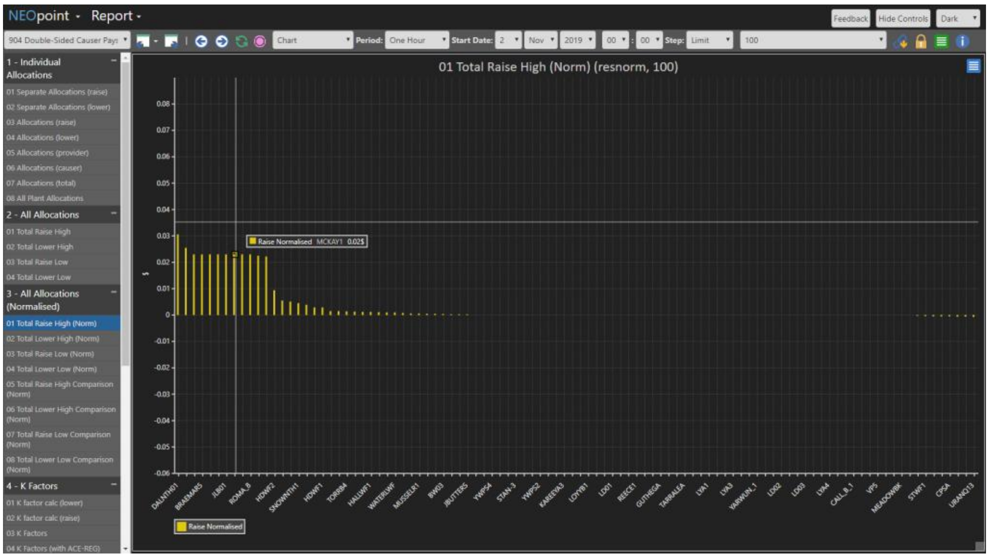


04 Total Lower Low

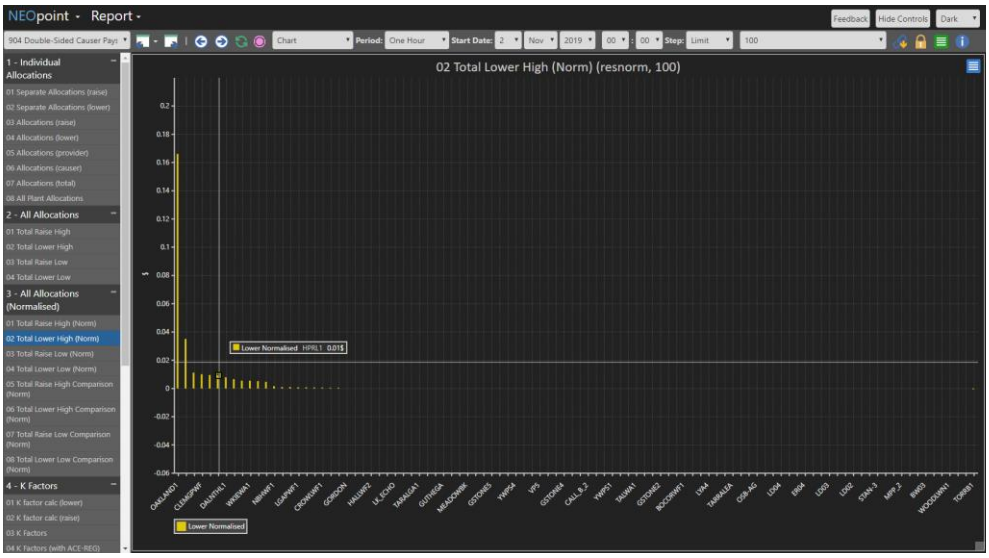


6.3 All Allocations (Normalised)

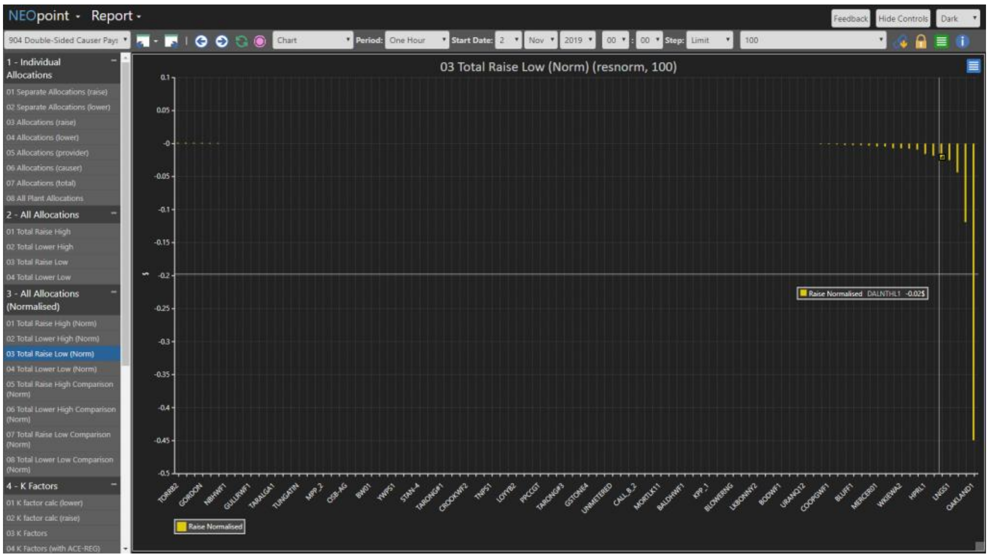
01 Total Raise High (Norm)



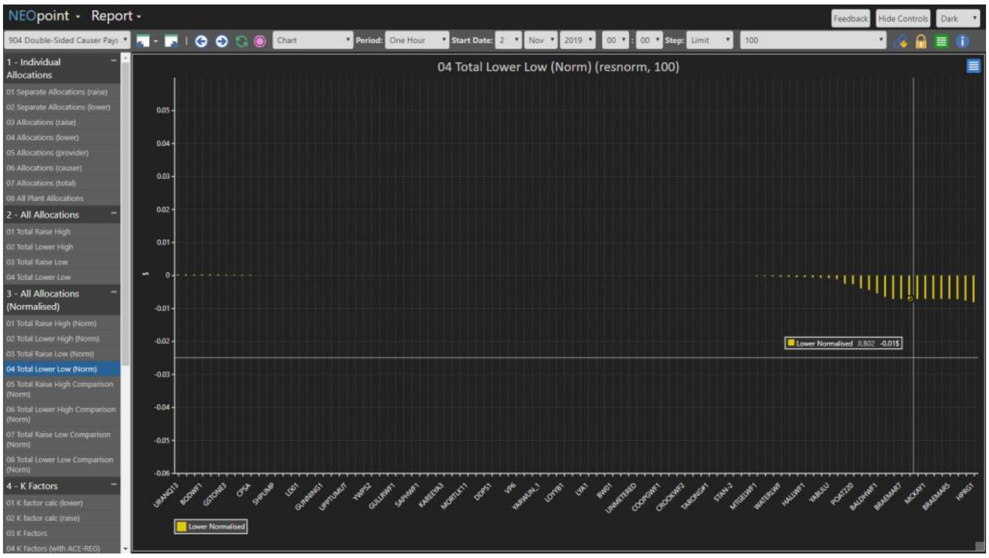
02 Total Lower High (Norm)



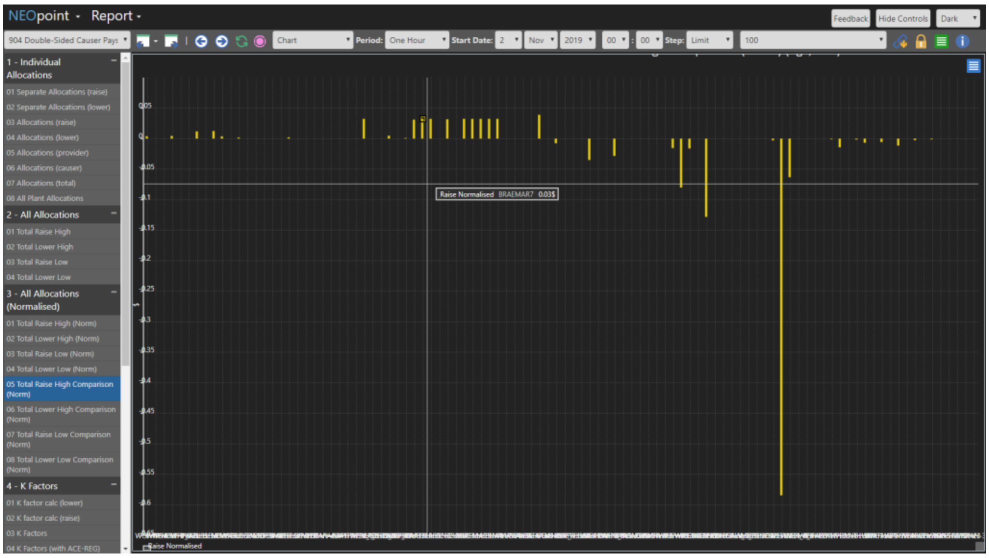
03 Total Raise Low (Norm)



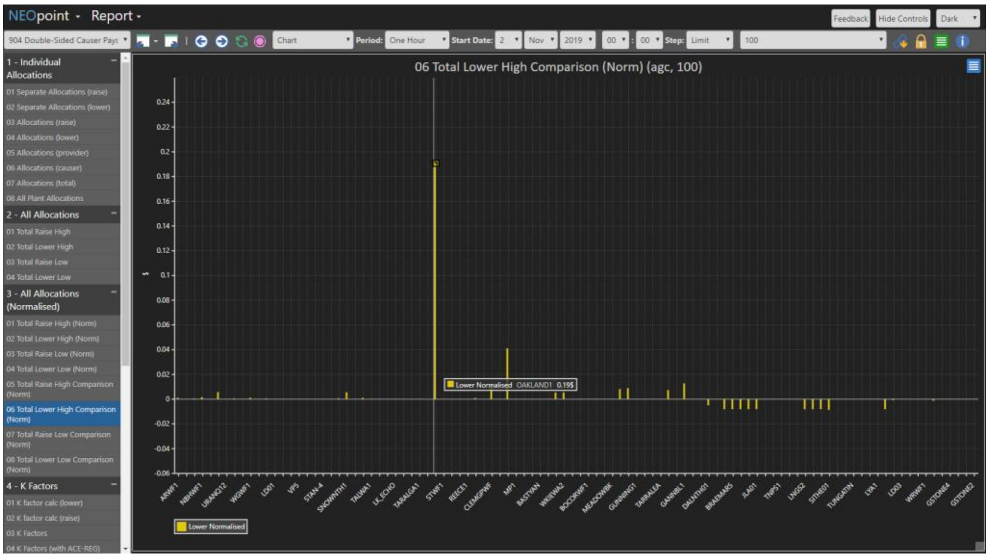
04 Total Lower Low (Norm)



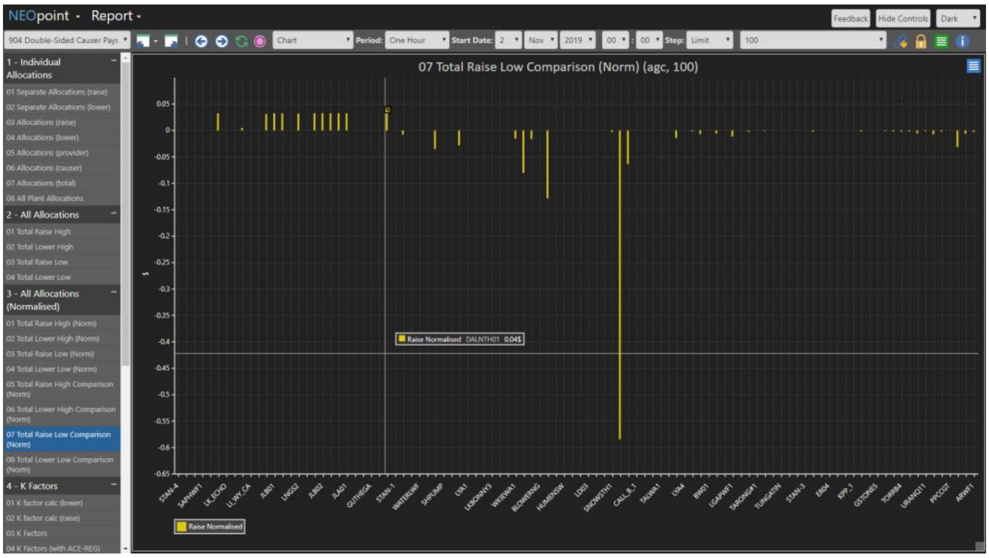
05 Total Raise High Comparison (Norm)



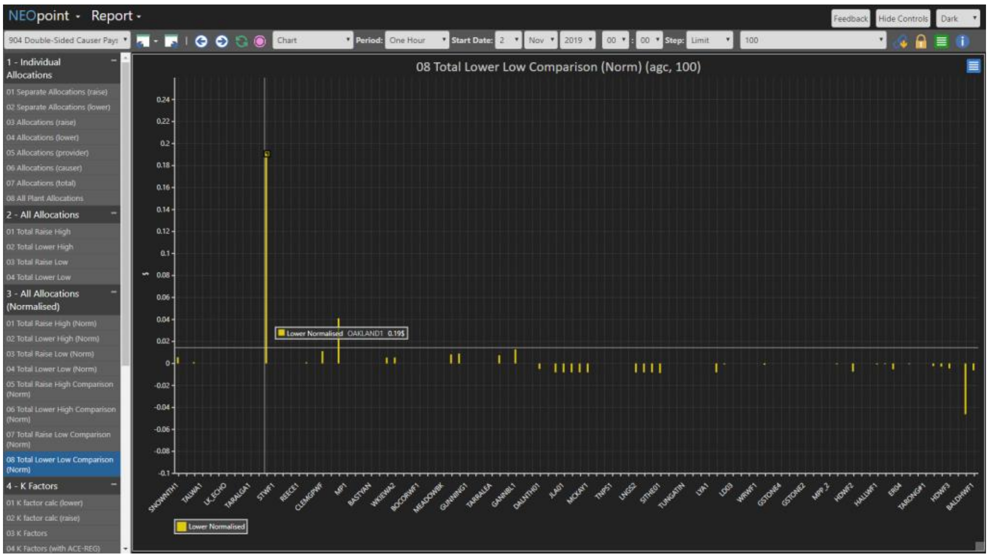
06 Total Lower High Comparison



07 Total Raise Low Comparison (Norm)

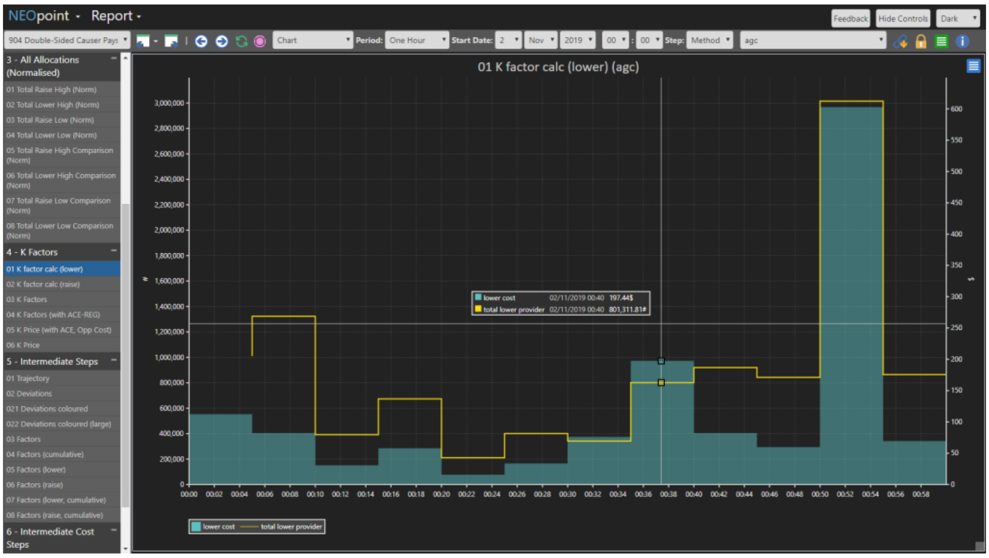


08 Total Lower Low Comparison (Norm)

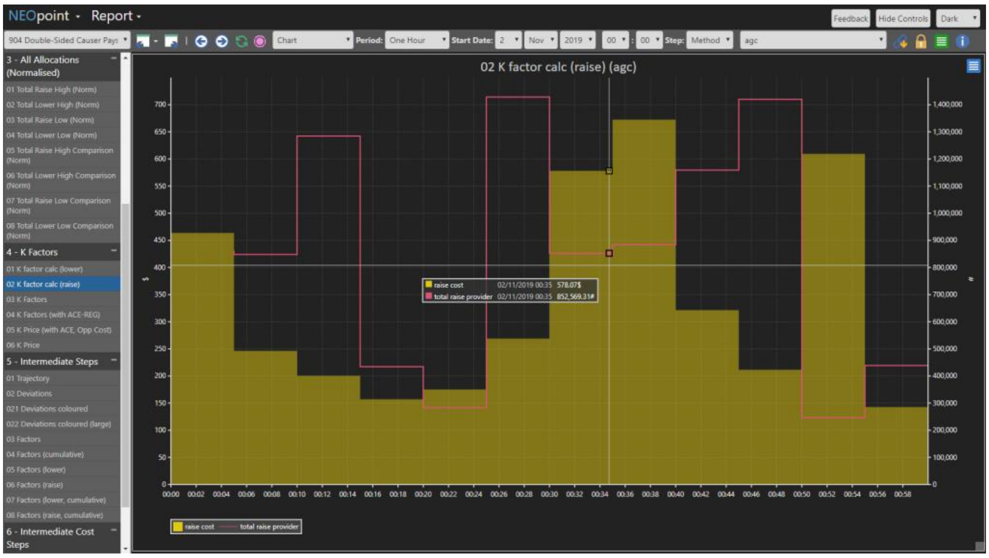


6.4 K Factors

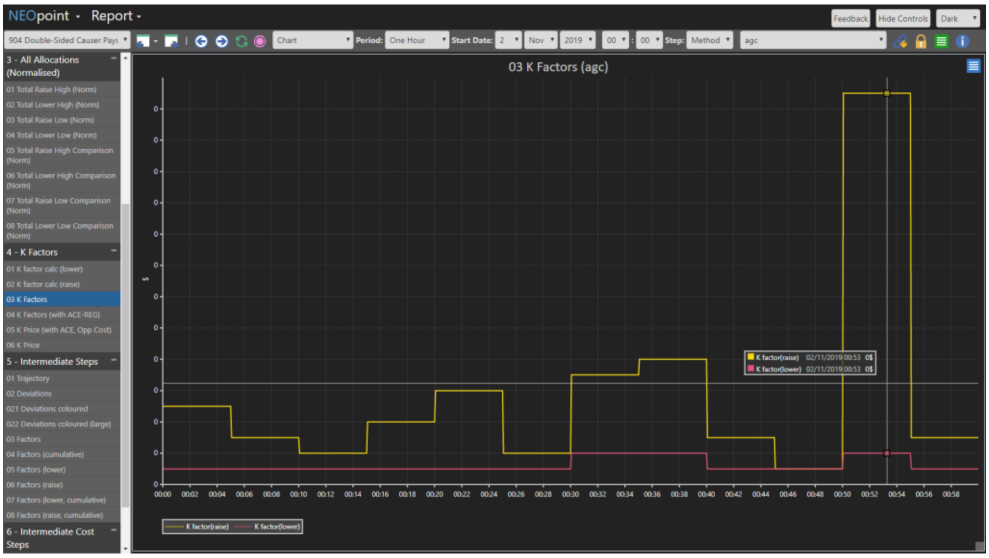
01 K factor calc (lower)



02 K factor calc (raise)



03 K Factors



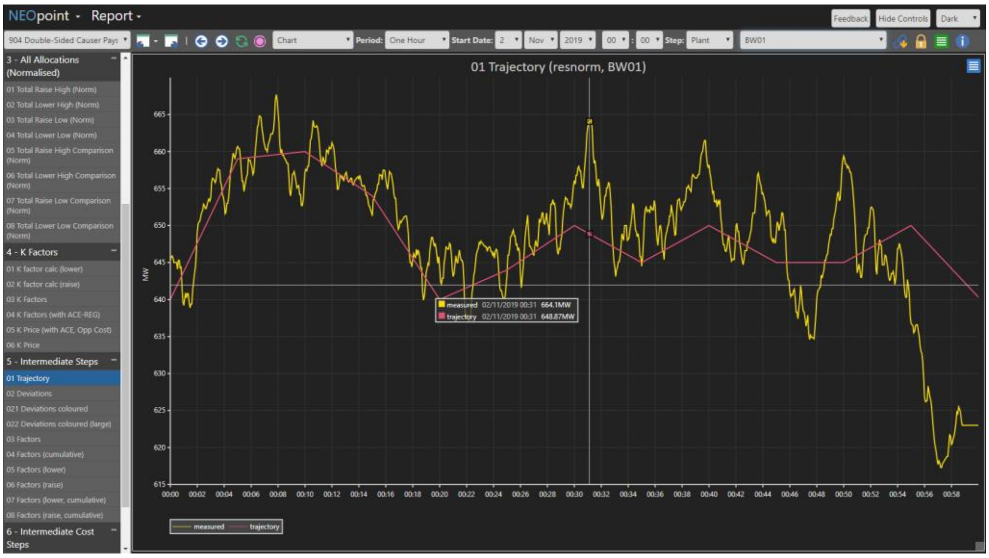
04 K Factors (with ACE-REG)

05 K Price (with ACE, Opp Cost)

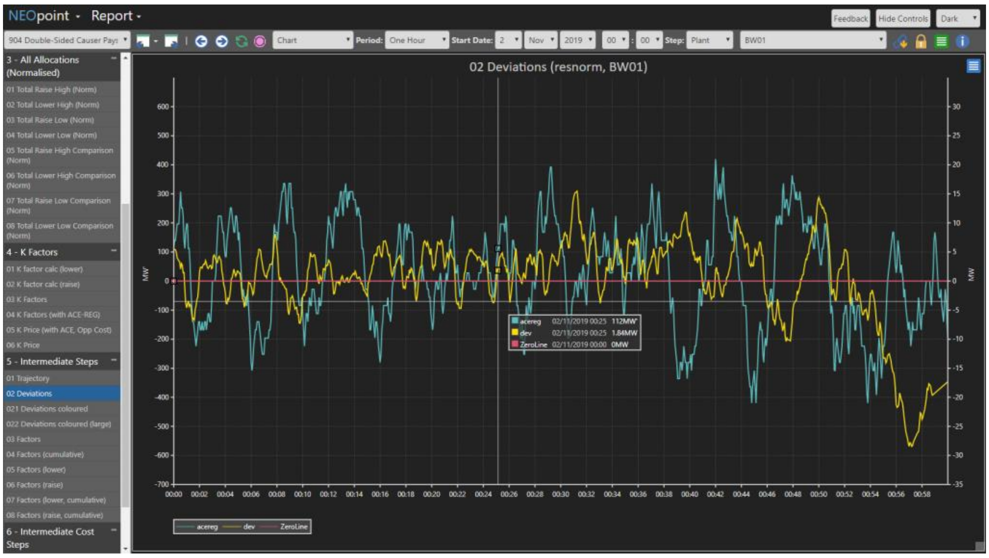
06 K Price

6.5 Intermediate Steps

01 Trajectory



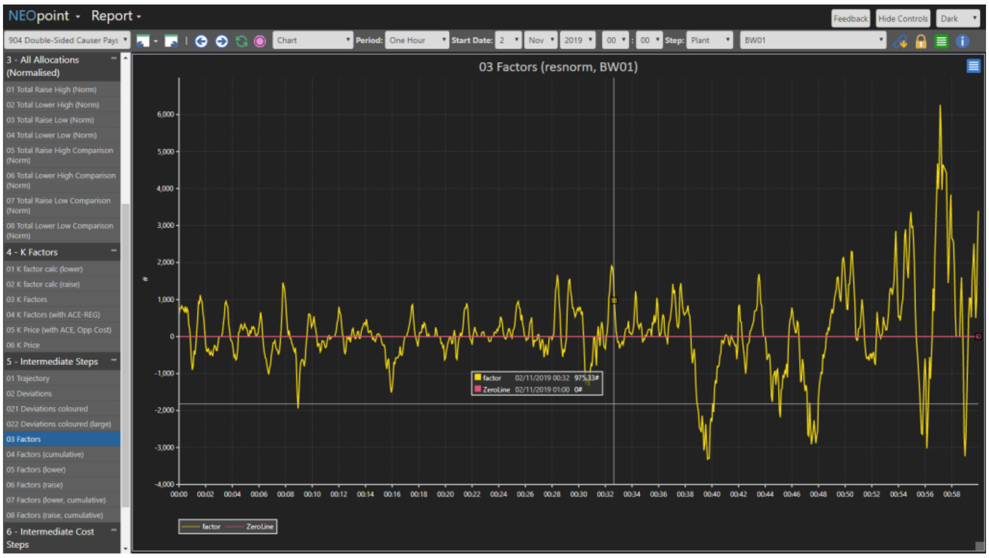
02 Deviations



021 Deviations coloured

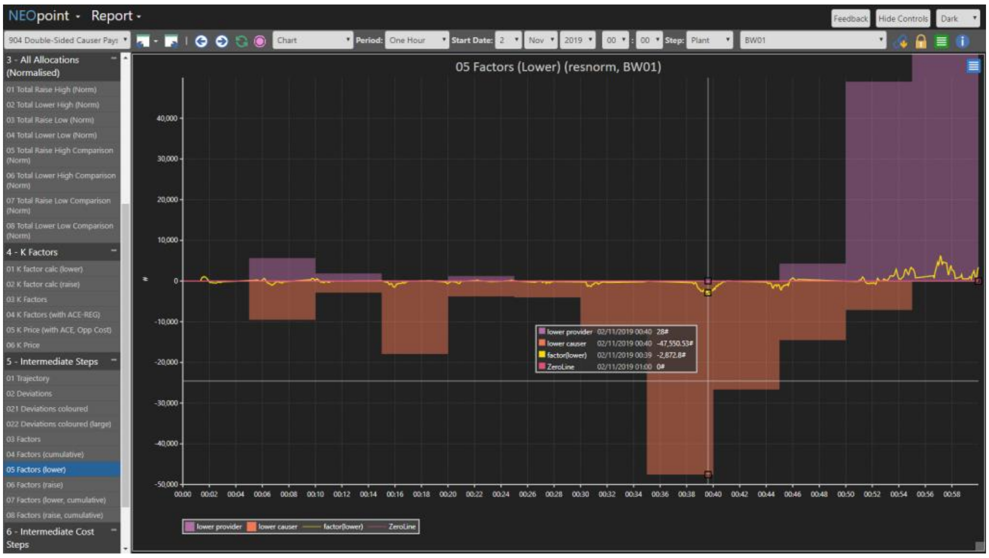
Note: At the time of writing, this type of chart is not implemented correctly in NEOpoint

03 Factors

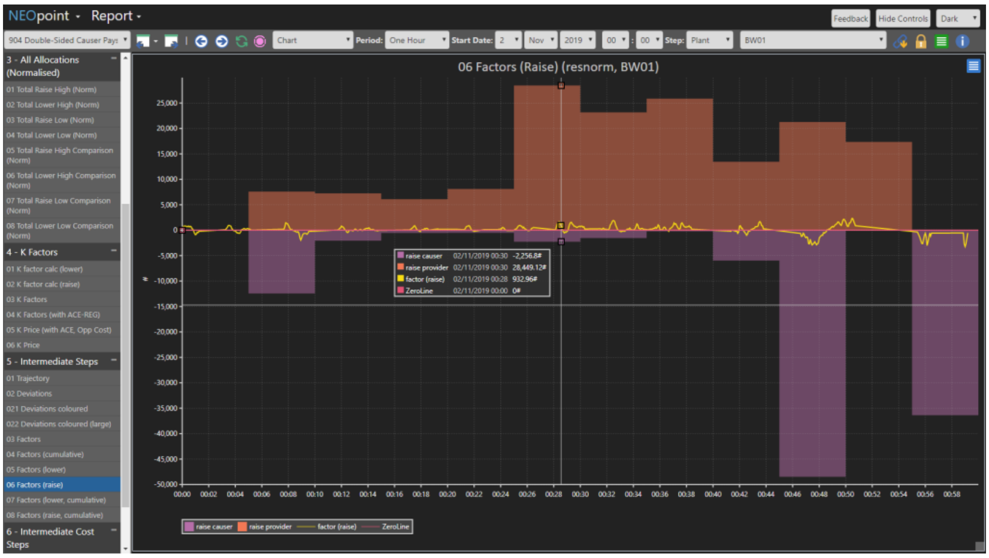


04 Factors (cumulative)

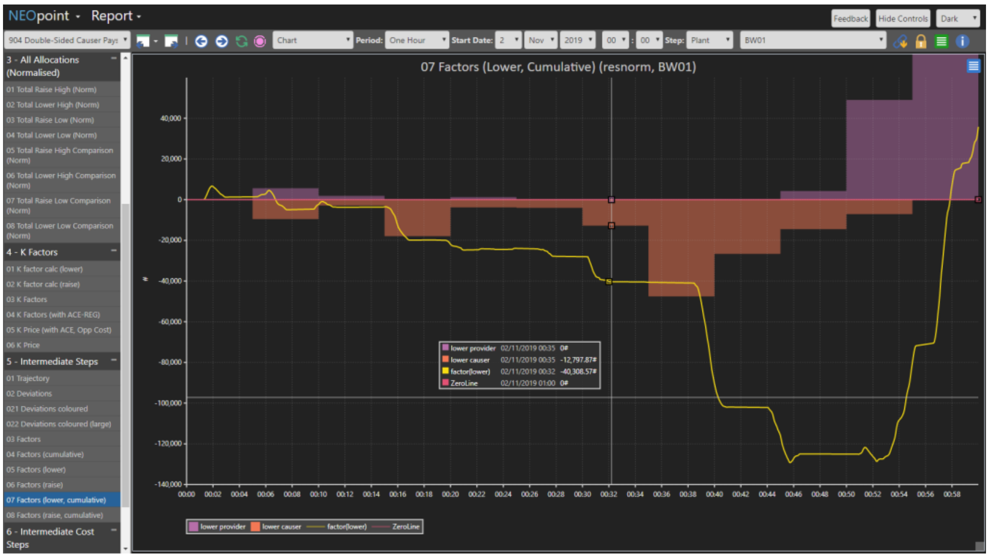
05 Factors (lower)



06 Factors (raise)



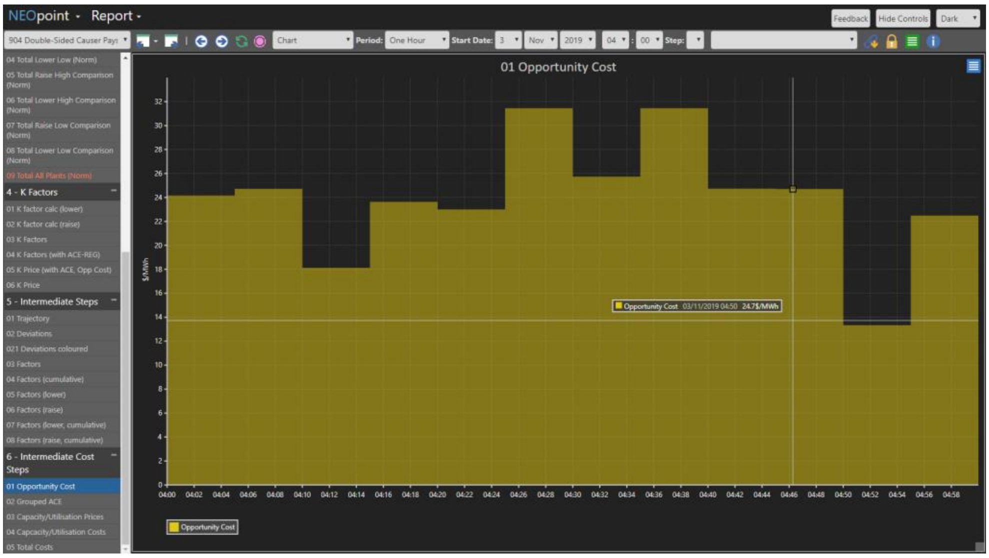
07 Factors (lower, cumulative)



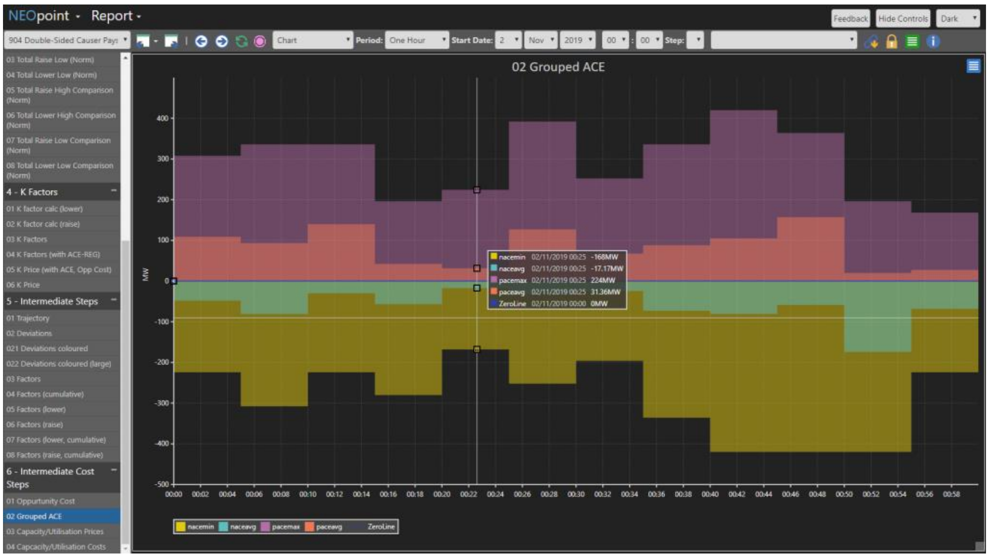
08 Factors (raise, cumulative

6.6 Intermediate Cost Steps

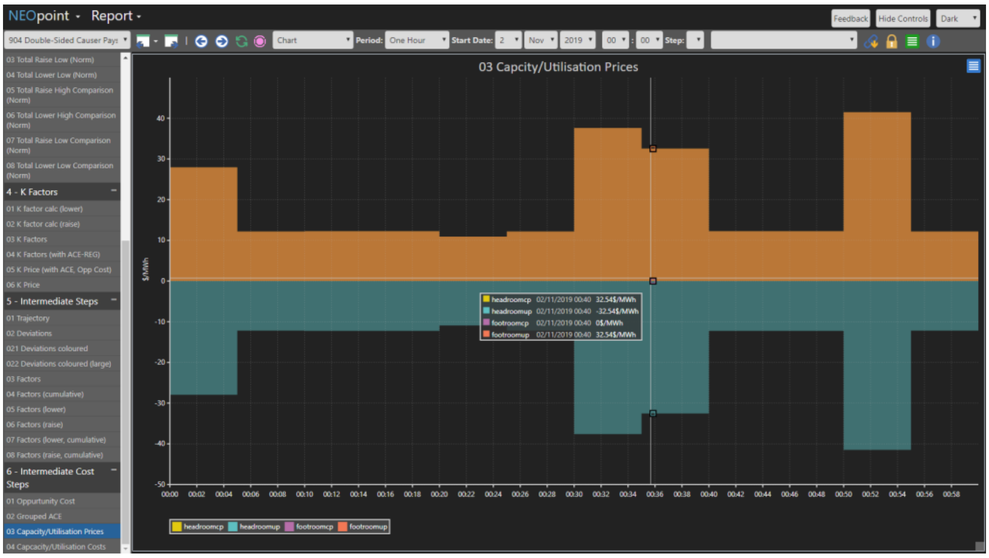
01 Opportunity Cost



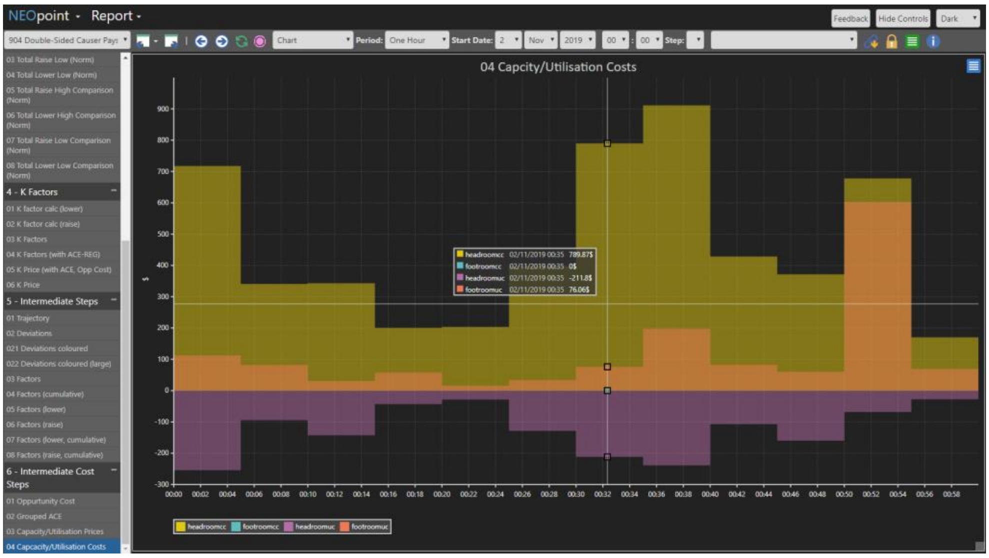
02 Grouped ACE



03 Capacity/Utilisation Prices



04 Capacity/Utilisation Costs



05 Total Costs