



A CONTROL ALGORITHM APPROACH FOR OPTIMIZING ENERGY RESOURCES THROUGH POWER GENERATION FOR A SOUTH AFRICAN STEEL WORKS PLANT

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ABSTRACT

Numerous engineering plants have varieties of processes, where individual process flows are dependent on previous processes and operated by default or manual settings. Initial raw material feeds may fluctuate over time, possibly resulting in inefficient use of energy resources. This paper describes a study on power generation capabilities of such a plant.

Off-gasses from various steel production processes are utilized in boilers; producing steam for the Works. Excess steam is used for power generation. The Works experienced unstable power generation, due to fluctuations in available steam. This resulted in regular turbine trips, causing power generation losses, additional gas flaring and reducing machine life expectancy.

To address this problem; off-gas and steam production data were analyzed over three months. A control approach was set up, where the algorithm's objective was optimum power generation, for a 5MW and 30 MW turbine. Results showed potential power generation increase over 26% was possible, still not eliminating trips. The algorithm incorporated the possibility of burning natural gas in a boiler, when needed. This scenario could have led to no trips and an increased generation capacity of over 48%. Additional power generation's financial impact overcame the high cost of utilizing natural gas for power generation purposes.

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1 INTRODUCTION

Numerous engineering plants consist of a variety of processes, where individual process flow rates are mainly dependent on previous processes and are mainly operated by default or manual operating settings. The initial raw material feed or flow input values are not necessarily constant and may fluctuate over any time interval, which may result in an inefficient use of energy sources over the whole spectrum of an industrial engineering plant. One such engineering sector is the steel production industry.

For the current works under investigation, Natural Gas and coal are burned as external energy sources, in various combinations with production off-gasses that form, i.e. Coke Oven Gas (COG), Blast Furnace Gas (BFG) and Basic Oxygen Furnace Gas (BOFG). These energy sources are used for production processes all over the Works, including steam generation. Steam is used throughout the Works for multiple process applications and excess steam is finally utilized for power generation. Continuous fluctuating process mass flows directly lead to fluctuating off-gas production, which results in inconsistent steam and ultimately volatile power generation. This fluctuating off-gas production and in a lesser sense, plant processes that have a changing demand for off-gas and steam use, set the scene for an unstable power generation and inefficient utilization of energy resources. Off-gas that is not utilized at the present moment is burned off into atmosphere through flares or bleeders. Even though power generation is not part of the core business, it has a direct financial impact on the work's net cost.

Inefficient use of energy sources, brought forth the quest to conduct a research study on how these sources could be optimized, setting up a universal control algorithm. One such control philosophy is by means of setting up a neural network (NN) for process control and optimization.

1.1 Neural Networks

Artificial Neural Networks (NN's) are problem solving techniques that learn from data and solve nonlinear models. For system modeling and identification, time series forecasting and control, the multilayer perceptrons (MLP's) and radial base function networks (RBFN's) are the most utilized NN's [1].

Bloch and Denoeux [1] presented two studies where NN's were used to control process optimization. The first study was to determine the inductive temperature at an induction furnace for a steel plant's hot dip galvanizing line. The second study was the control of a clotting process in water treatment plant, where raw water was purified to produce drinking water.

Castellano and Fanelli [2] used a NN model to determine what input variables were needed to create a model and what inputs may be rejected. Their network commenced by using all available inputs, creating a model and then worked backwards, removing the unnecessary nodes. Weights were assigned to each input node, which might vary as input nodes were removed, in order for the simulation results to stay virtually the same.

The quality of a NN optimization model depends not only on the model validation, but also legitimacy of the data used to set up the model. Ensuring correctness of data plays a vital part in NN design and the need may arise to generate additional and complementary experimental data [3].

According to Simutis *et al.* [4] the grounds on which a process optimization model must be investigated, is the ratio of benefit over cost that the model brings. Hybrid modeling seemed to be most fitting for production processes.

2 OPTIMIZATION STUDY ON POWER GENERATION POTENTIAL FOR A STEEL WORKS

A study was conducted on the power generation capabilities of a steel works. The sole purpose of the study was to investigate the additional potential power generating capabilities from off-gases.

The study focusses on how available off-gasses could have been utilized for steam and therefore extra power generation. Measured data is used to develop a control algorithm on what could have been done to improve power generation. This study forms the basis of a follow up study, where a NN will be set up to statistically predict what the following flow values might be, within a confidence interval. Accurate prediction will lead to accurate control.

Off-gases are production by-products that possess a significant formation enthalpy, i.e. the ability to be utilized as fuel. These gasses are burned in a boiler houses to generate steam. Steam is mainly used in various plants processes and excess steam may be used for power generation.

The works find power generation to be unstable, due to fluctuations in available steam. This instability causes turbines to trip regularly, not only ensuing power generation loss to unused steam or additional flaring, but also decreasing the life expectancy of these rotating machines. A turbine is designed to be kept in continuous operation and only be stopped and taken off-line for general overhauls and inspections, once every three to five years. For this works shortage has made it a common occurrence to have a turbine tripped once every three to seven days.

At the time of the study, the works had three power generation turbines, i.e. a 5MW, 30MW and a 40MW Turbine-Generator (TG) set. Both the 5MW and 30MW TG operate on 30bar steam and the 40MW uses 66bar steam with an additional steam injection at 16bar. 66bar steam is generated by two Kilns, the High Pressure Boiler House (HPBH) produces 30bar steam and 16bar steam emanates from four low pressure Kilns and also 30bar steam that gets de-superheated.

Initially the works consisted of only two different steam productions, namely 16bar low pressure (LP) steam and 30 bar high pressure (HP) steam. Power was generated with a 5MW and 30MW TG set. Years later an additional 40MW TG set, utilizing 66bar steam, was installed.

The 5MW and 30MW TG sets both operate at an efficiency of 5tons/MW. For the 5MW to stay operational a minimum flow of 10tons/h is necessary and the 30MW will trip for flow below 30tons/h. The 40MW operates at an efficiency of 3.9tons/MW for the 66bar steam, with the capacity to generate 30MW, where the additional 10MW is generated from 16bar injection steam at an efficiency of 7tons/MW.

The perception from management was that off-gas and not steam production capabilities were the limiting factor and therefore not much could be done about the situation at hand.

2.1 Off-gas and Steam production

Hourly COG, BFG and steam production data were analyzed for a three-month period, ranging from 1st of March 2011 till June 6th 2011 (from here on referred to as 'the period'). The logged readings represent the average readings over the hour and not an instantaneous flow rate value. The authors acknowledge that finer time interval measurements will be crucial for a real time control algorithm, since hourly averages might smooth out outlier data points, leading to a misrepresentation of the data.

In Figure 1, the total HP steam production during this period is depicted over time. Fluctuations in steam production are evident from the figure and it can be observed that these fluctuations do not necessarily follow a clear pattern.

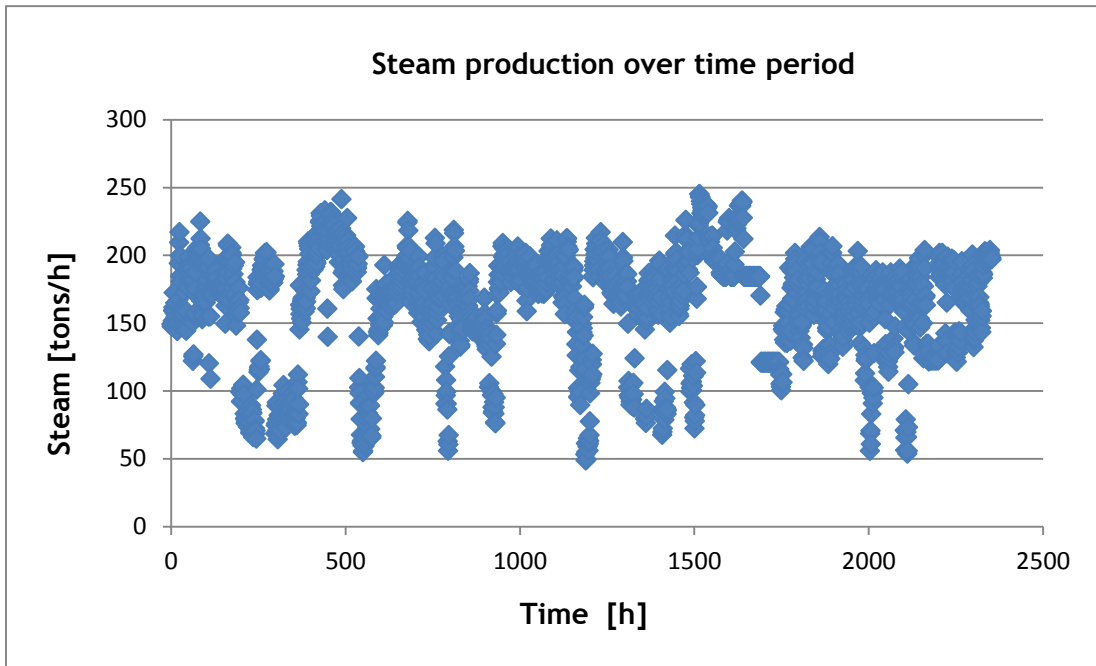


Figure 1: Actual average steam production flow rates [tons/h] plotted over time [h] for the period

Unlike for a power station, the main reason for steam production at a steel plant is not power generation, but for various process necessities and uses all over the works. As mentioned, only excess steam, after plant demand, may be consumed for power generation. Figure 2 depicts the available steam for power generation during the period.

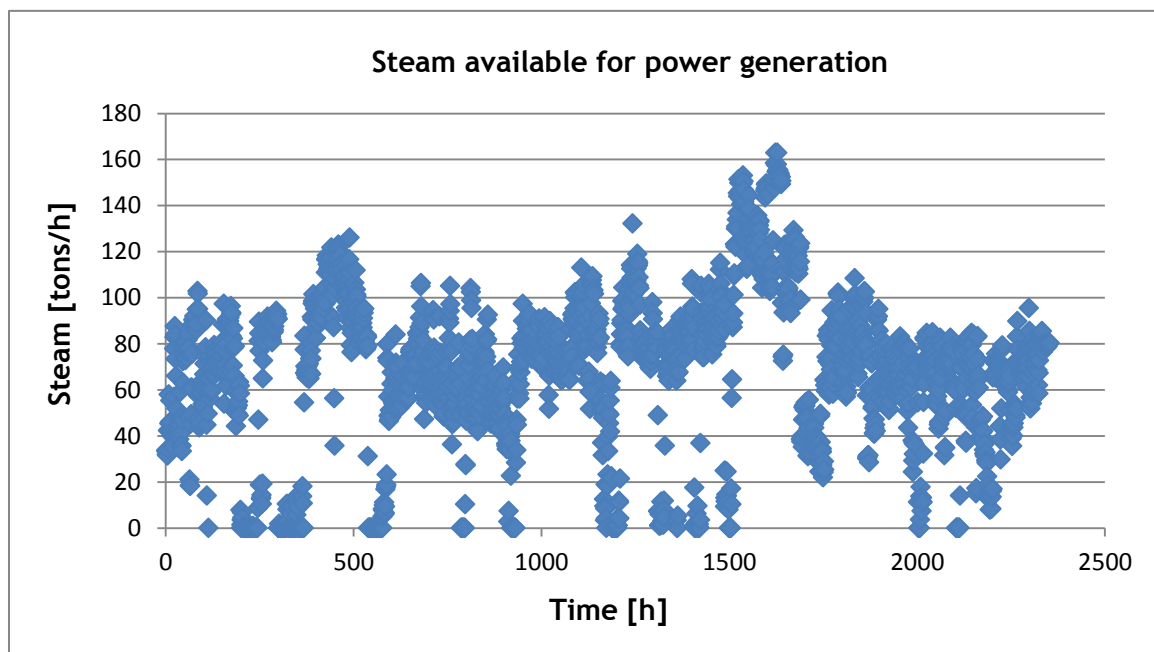


Figure 2: Steam [tons/h] over time [h], available for power generation

As in Figure 1, the fluctuations depicted in Figure 2 are unmistakable, but a pattern similarity to Figure 1 is observed. The related patterns may be contributed to a plant steam demand that does not vary drastically over short time intervals.

2.2 Power generation and the control algorithm

Common operating practice is to set the 5MW TG set at a set point of 20tons/h, irrespective of what the flow might be. This creates the scenario where the turbine cannot receive more steam, even if sufficient off-gas is available to produce the steam. This operating procedure also results in more 30MW trips, from low steam availability conditions. A tripped turbine will only be put back into operation, once a continuous period of not shorter than 15 hours of sufficient steam is evident. The 15 hours depend on operator observation and may stretch far longer, especially for night and weekend shifts. A schematic layout of the operation procedure is given in Figure 3.

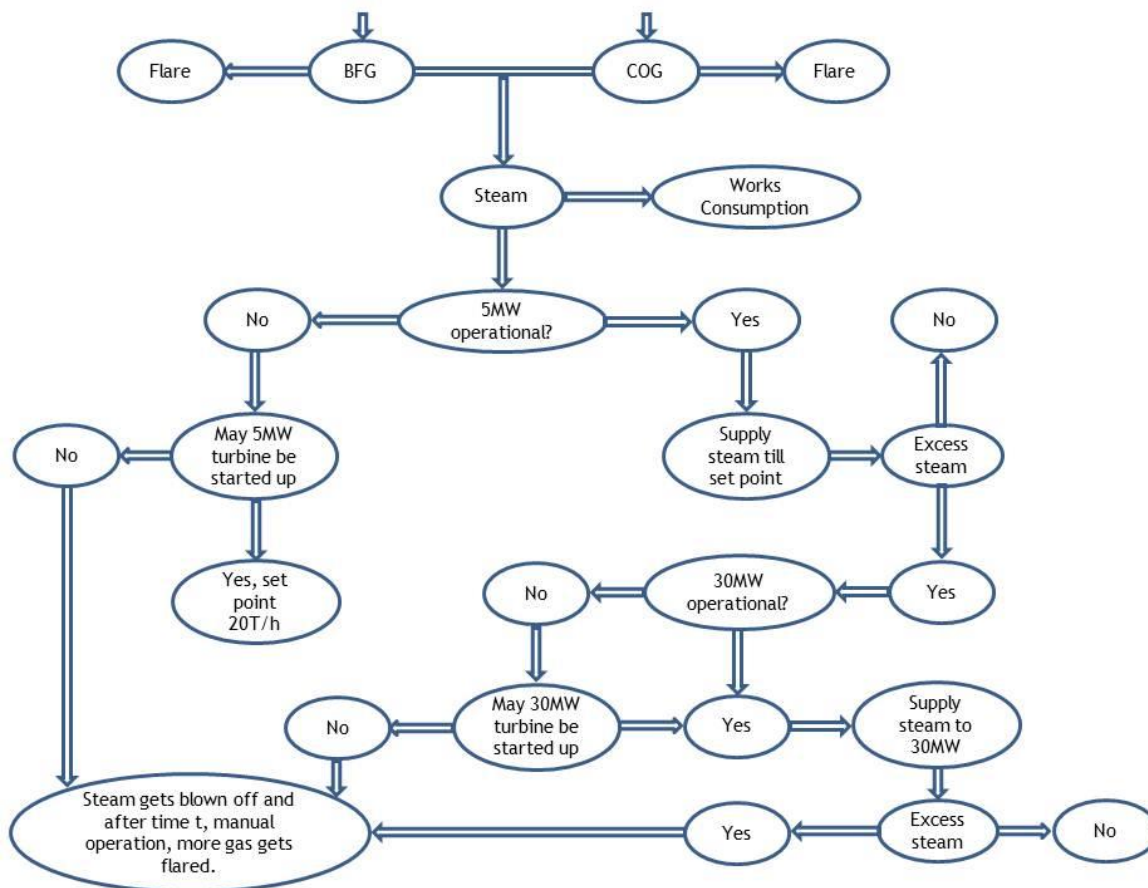


Figure 3: Schematic layout of power generation setup

Figure 4 represents the combined power generation, for the 5MW and 30MW TG sets, over the period for the above mentioned operating philosophy.

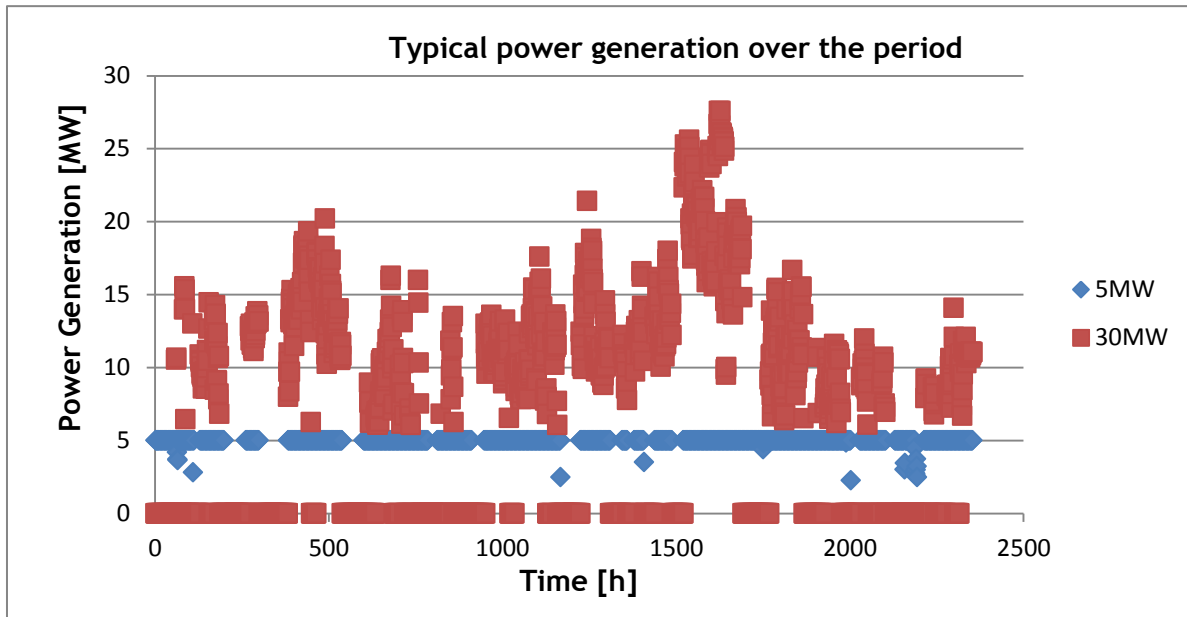


Figure 4: Typical power generation for the 5MW and 30MW over the period, plotted against time [h]

For this time period, under the plant operating procedure, the proposed power generation from the 5MW TG set was on average 3.88MW and the 30MW would have been able to master an average of 5.89MW. The combined power generation would yield 9.77MW out of a possible 35MW. The 5MW machine would have tripped 14 times over the three months and the 30MW would have experienced 32 stop and start conditions.

A control philosophy was set up, where the algorithm's main objective was to ensure optimum power generation with the available steam at hand. The algorithm will use the potential steam data and decide how to divide the steam between the TG sets and also which turbine to trip, when there is not sufficient steam to keep both machines at the minimum functioning point. Decisions are made based on the analysis of data prior to the current situation. Included in the algorithm optimization, are the turbine efficiencies. Figure 5 depicts a broad representation of the control philosophy's structure.

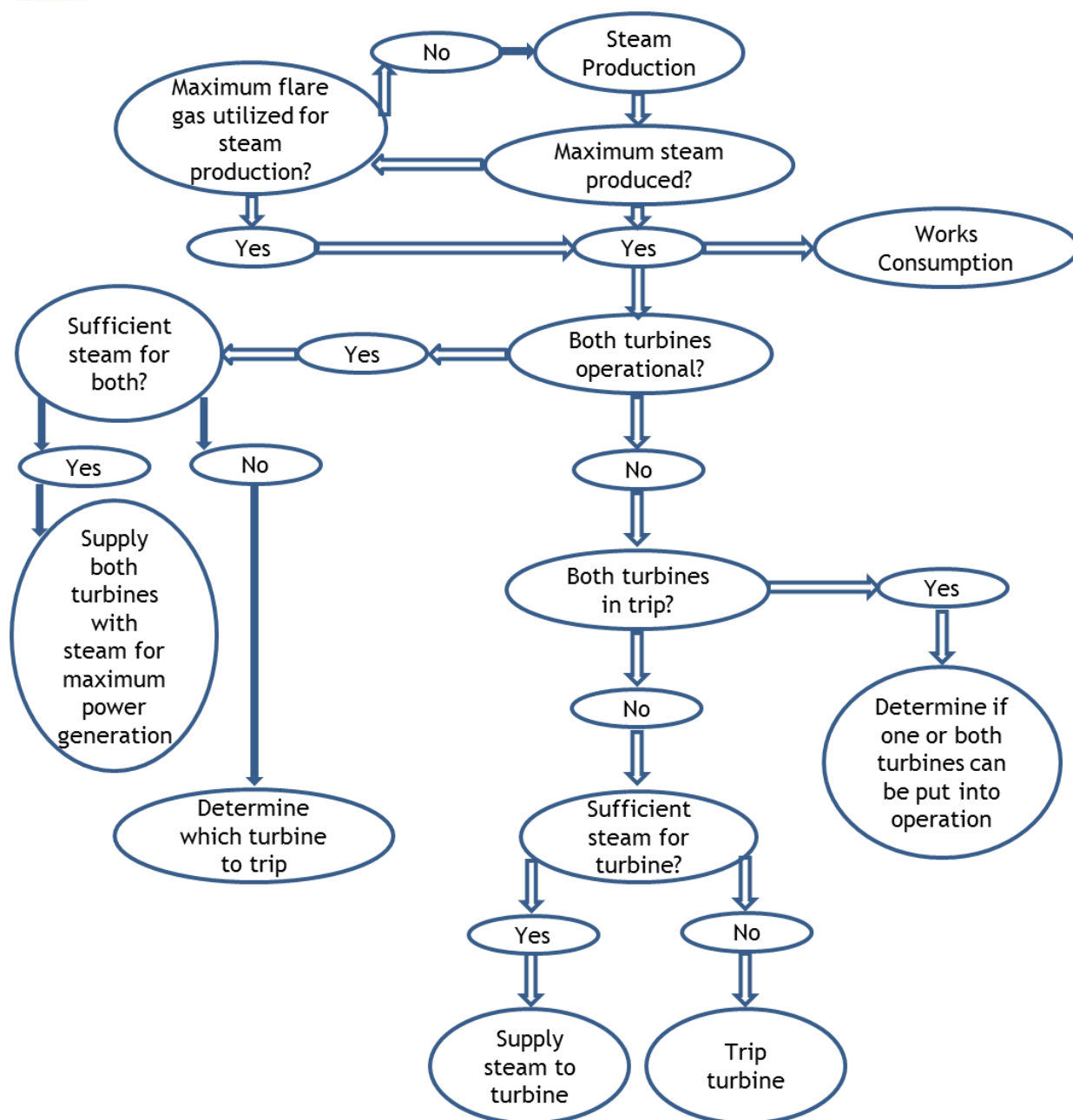


Figure 5: Broad layout of control algorithm

Figure 6 illustrates how power generation would have turned out under controlled conditions. On average, the ability to generate electricity would have decreased for the 5MW from 3.88MW to 3.54MW, while the 30MW would have seen an increase from 5.89MW to 8.85MW. The overall result would have been a total generation 12.39MW, 2.62MW above the plant expectation. This increased power generation, with optimized control philosophy, would have seen the 5MW being tripped 33 times (compared to 14), over the three month time period, whereas the 30MW would have experienced steam shortages on 21 occasions, compared to the previous 32.

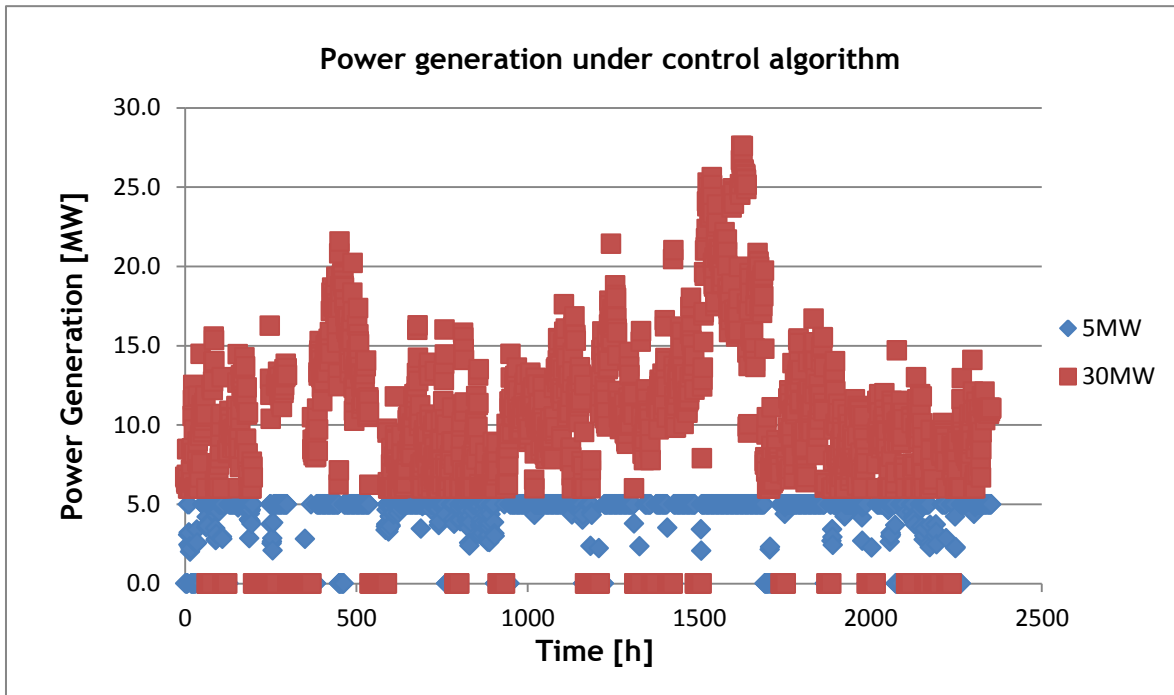


Figure 6: Power generation over time for optimization control philosophy for the 5MW and 30MW

From the data and everyday practical experience it is evident that there are occurrences where steam shortages will result in a machine trip for one or both turbines. The available steam, even if it is inefficient to produce power, is wasted. Taking into account that sufficient steam is necessary for a minimum of 15 hours to restart a TG set, rather large potential power generation losses may be incurred. It must be noted that if only one TG set is operational, the steam will only go to waste, once full power generation capacity is obtained for this operational TG set.

2.3 Incorporation of Natural Gas in the control algorithm

In an attempt to investigate and address the potential impending losses, the simulation conveyed the possibility of installing Natural Gas (NG) burners at the HPBH. NG will be used to ensure that both turbines will receive the minimum quantity of steam to prevent all steam shortage trips. It must further be noted that the control algorithm will always seek to optimize the system; therefore the fixed amount of steam per 5MW practice does not hold.

In Figure 7, the proposed power generation is plotted over time, where NG is burned as an additional energy source. As expected, the simulated results for Figure 7 are similar to the obtained results for Figure 6, with one large difference; no turbine experiences a trip condition. The question may arise as to why NG is not being used to simply ensure that both TG sets operate at full designed capacity? Power generation by means of NG is far more expensive than to just buy electricity from Eskom and therefore, the additional generation gain must outweigh the heavy input cost from an economical point of view.

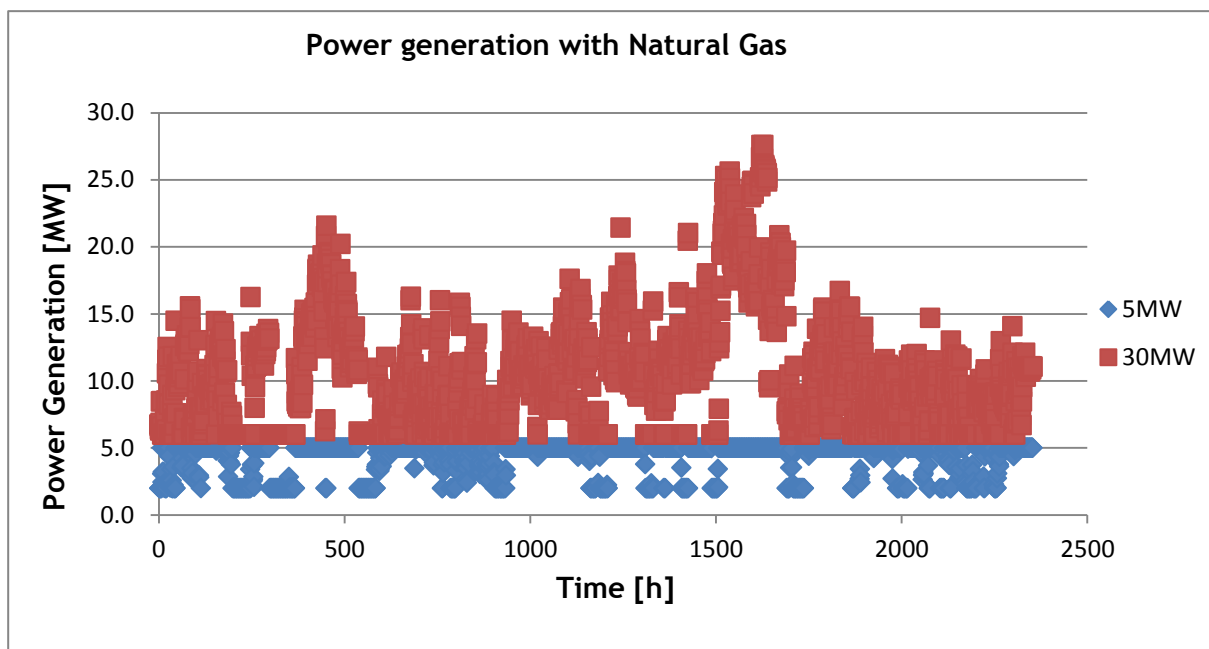


Figure 7: Power generation while using NG as additional energy source, plotted over time

The anticipated power generation, with NG present, yields a simulated result of 4.32MW compared to 3.54MW for the 5MW TG set. The 30MW will see a proposed increase from 8.85MW to 10.21MW. A rise of 2.15MW is proposed for the use of NG, where NG contributes 1.20MW and previous lost steam 0.95MW of the further generation. During the study period, the works paid approximately R360/MW-h to Eskom and using NG for power generation would have yielded a cost in the region of R800/MW-h, taking into account the HPBH and HP TG efficiencies. Plant costing data available showed that the maintenance cost per trip for the 5MW was over R8000, whereas the 30MW could be placed at about R12100 per trip. With these costs taken into consideration, the use of NG would have led to an annual gain of more than R450000, with respect to the control algorithm without NG.

2.4 Investigation of flared gasses

Figure 8 shows the amount of steam that could have been generated from the flared Coke Oven Gas (COG) and Blast Furnace Gas (BFG). The assumption is made that all of the COG may be utilized for steam production and 95% of the BFG. The remaining BFG will be flared for line pressure control purposes. More BFG than COG are produced over the works and the rate of flow in m³/h for BFG over COG for the period was a factor of 15.35:1.

The potential in HPBH steam generation, for flared gas only, amounts to 25.27MW. Apart from ill control, boiler house capacity is a limiting factor and an additional 25.27MW were not entirely possible. The Works started off with 6 HP boilers, all with the potential to generate 65tons/h. At the time of the study, four boilers were operational, amounting to a steam generation capacity of 260tons/h.

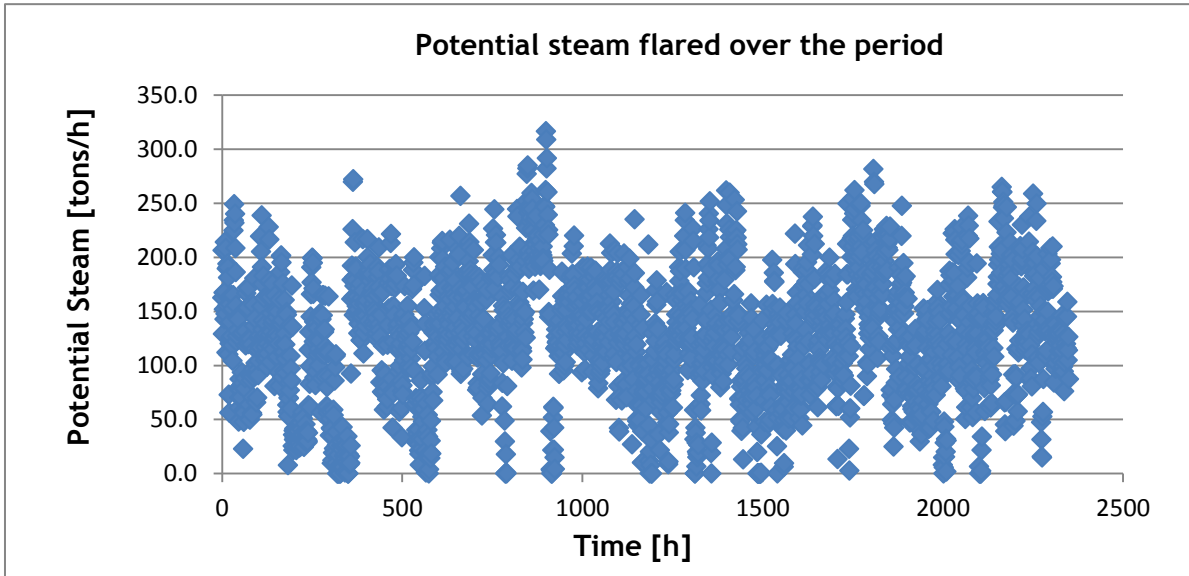


Figure 8: The potential steam capacity that was flared during the period

If the HPBH capacity is taken into consideration and the 5% restriction on BFG for pressure control, Figure 9 displays the potential steam for power production that could have been available. Using this steam production for power generation, in combination with the control algorithm, the 5MW would have been able to generate 4.60MW, trip 12 times and the 30MW power generation would have had a steep increase to 24.29MW.

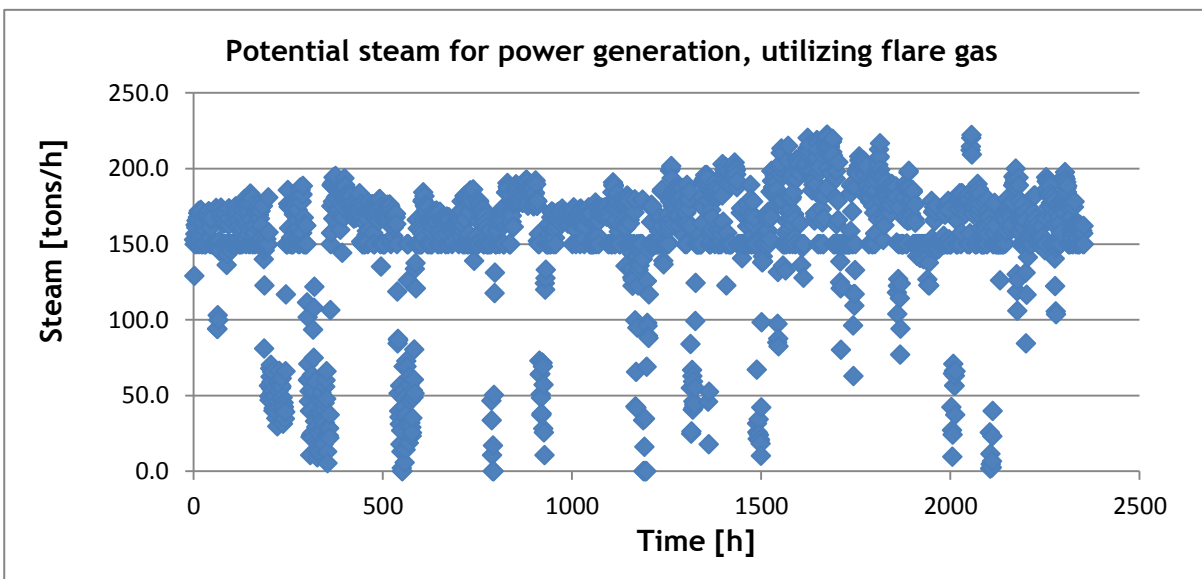


Figure 9: Potential steam for power generation if flared gas was used to HPBH capacity

Figure 10 represents the power generation that would have been possible if the HPBH was used to full capacity with the accessible BF- and COG and also the utilization of NG.

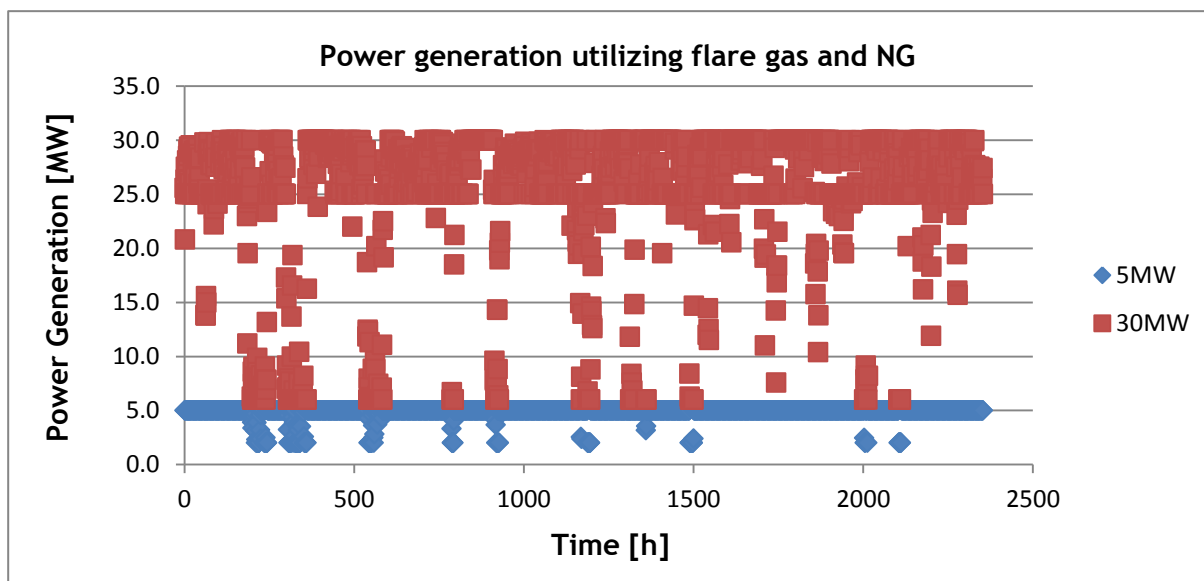


Figure 10: Potential power generation over time, utilizing flare gas and NG to prevent steam shortages

The energy producing capability of the 5MW TG set could have reached a value of 4.85MW over the period, while the 30MW machine could have seen an average of 25.31MW during this time interval. Due to NG a total of 1.27MW would have been generated additionally, where only 0.23MW would come from NG and the remaining 1.04MW from steam losses.

2.5 Comparison of results

The isolated situations of the HPBH and flared BF- and COG have been discussed. A simulation program was set up to determine what the typical power generation capabilities were over the time period. The program perceived what would realistically have happened and could have happened in a controlled environment, where off-gas steam production and steam flows to the turbines are managed. It must also be mentioned that the actual generation would probably have been even lower than the simulated values. A 15-hour interval will be far exceeded on some night and weekend shifts. Furthermore, operating staff have no indication on whether sufficient steam was present for 15 hours, resulting in biased decision making.

Table 1: Comparison of different power generation combinations

Situation	5MW [MW]	5MW trips	30MW [MW]	30MW trips	Total [MW]	NG financial impact [mR]	Financial impact to initial situation [mR]
Initial	3.88	14	5.89	32	9.77	-	-
Control Algorithm	3.54	33	8.85	21	12.39	-	8.262
Control Algorithm with NG	4.32	0	10.21	0	14.53	0.460	8.722
Flared Gas with Control Algorithm	4.60	12	24.29	13	28.89	-	60.297
Flared Gas with Control Algorithm and NG	4.85	0	25.31	0	30.16	3.424	63.720

A further step was taken and the hypothetical question was asked what the impact of additional NG burners could have been, in times of steam shortages. After the possibility of NG for the setup has been investigated, the attention shifted to BF- and COG that were flared into the atmosphere and yet again the influence of NG for this particular situation. Table 1 portrays all the simulated values that were obtained by way of the control algorithm. For every occurrence the proposed power generation and number of trips were tabulated, together with the financial impact from the simulated situation in comparison to the plant's status quo.

From Table 1 it is apparent that the introduction of a control algorithm, could have contributed to a positive financial impact in the order of R8.3 million per annum. As mentioned, these values were obtained on 2011 costs and the current real values will be larger, due to electrical tariff increases. The larger financial gain would have had an offset of more turbine trips. Even though a common occurrence, a turbine trip should not be taken lightly. It was mentioned earlier that the power generation turbine is not developed to have stop-starts in operation and each trip has a negative influence on the rotating machine's life span. The use of NG might have an initial cost and would only contribute an additional income of less than R500000, but it would serve a higher purpose, insurance against trip conditions and therefore protection of the TG sets.

What is more apparent from the simulated results, is the potential positive financial impact, if not only the steam flow to the turbines could be managed, but also the vast amounts of energy being flared to no avail. If the BF- and COG flows were better controlled and optimized for maximum steam generation, power generation might have experienced an additional financial gain of just over R60 million per annum and a gain slightly less than R64 million per annum, if NG was used to utilize all the potential energy and protect the turbines from steam shortage trips.

The representation of data thus far was only what happened at the HPBH, and the amount of flared gas. The simulation program also included all possible flows to the 66bar TG set, and

the ability to introduce new TG sets into the program, to find the hypothetical optimum power generation scenario for the works. The incorporation of these scenarios and effects thereof was not discussed in this paper.

2.6 Actual power generation

It should be noted that the actual power generation was never compared throughout the paper. Due to the start-stop operation of the turbines and time in operation, both turbines' condensers had leaks to atmosphere. The 30MW was limited to a maximum, inefficient, power generation capacity of not more than 6MW and the 5MW turbine experienced a catastrophic failure in May of 2011, destroying the machine and emphasizing even more the importance of the exploiting NG for protection purposes.

During a trip phase, after the steam supply was cut off, an electrical fault led to the turbine being driven by Eskom power. Since the condenser was filled with incondensable air and not only condensable steam, unable to create a low pressure after condensation, rotating energy was transferred to the surrounding air. The heated air melted away four of the fifteen blade rows, three stator rows, damaging not only blades, but also the rotor.

The 5MW was due for a general overhaul in September of 2011, for an amount of R25 million. The damage was estimated at R40 million for a machine worth R50 million and it ended up being scrapped. Plant operation directly led to this damage.

3 CONCLUSION

The proposed study for the works was a control philosophy than does not only monitor and optimize the power generation, but energy resource management over the whole works. There are important factors to take into consideration when the control algorithm is examined, i.e.

- The data that was used was averages over an hourly interval. One second intervals may fluctuate even more than what was observed over an hour.
- The model works backwards and realizes what could have been done. A real life model will have to predict what is about to come, within a certain confidence interval and then arrange the flow over the works through control valves to the desired flow quantities. A further study is underway to set up such a prediction model, to be incorporated for the works.

The next phase will attempt a real life control algorithm. The algorithm must have accessible data to simulate statistical flow distributions and predict how to direct all available energy sources for the next time step. Necessary corrections will have to be made in the time step for adjustments and the newly received data will be worked into the statistical prediction model or Neural Network for future predictions. The model will also have to be flexible for future, external events, i.e. the knowledge for instance of when a blast furnace will receive a new slab.

4 REFERENCES

- [1] Bloch, G. and Denoeux, T. 2003. Neural networks for process control and optimization: Two industrial applications, *ISA Transactions*, Vol.42, pp 39-51.
- [2] Castellano, G. and Fanelli, A.M. 2000. Variable selection using neural-network models. *Neurocomputing*, Vol. 31, pp 1-13.
- [3] Coit, D.W., Jackson, B.T. and Smith, A.E. 1998. Static neural network process models: Considerations and case studies, *International Journal of Production Research*, 36(11), pp 2953-2967.
- [4] Simutis, R., Oliveira, R., Manikowski, M., Feye de Azevedo, S. and Lubbert, A. 1997. How to increase the performance of models for process optimization and control. *Journal of Biotechnology*, Vol. 59, pp 73-89.