

Conceptual Design of a Natural Gas-based Integrated Industry Park

Chen Chen*, Ross Wakelin

Northern Research Institute Narvik A.S., Postboks 250, N-8504 Narvik, Norway
chen@tek.norut.no

This paper describes the application of process integration and optimization to the conceptual design of an integrated chemical complex with natural gas and locally sourced minerals as the main raw materials. Different processes are available for converting natural gas to synthesis gas, with different ratios of hydrogen to carbon monoxide content. The economies of scale make it worth investigating a central synthesis gas plant supplying different downstream processes, matching their different demands for hydrogen or carbon monoxide. The study aims to select appropriate combinations of process type and production scale, and optimize the exchange of materials and energy.

The methodology applied is to construct a spreadsheet model containing the different processes and material and energy exchanges estimated mainly from literature sources. The relationships between the key process variables are described in the spreadsheet, and linearized (piecewise if necessary). The optimization of the selection of process alternatives, and values of the variables is then made using mixed-integer linear programming (reMIND and CPLEX) and the results returned to the spreadsheet model. The process is then repeated with sensitivity analyses on key variables. The objective function is defined to maximize the profit while taking account of carbon dioxide emission tax scenarios.

The initial phase of the project has identified potential capital cost savings from integrating different syngas-utilizing processes with a common syngas plant. Sensitivity of the optimized result to variations in raw material costs is presented. Development of the model for process design alone is probably not justified, however the model also can be applied to the identification of optimal responses to unplanned stops of individual processes. This can be used to make a fair and transparent system for apportioning the benefits (and cost/penalties) arising from process integration of separate processes. This is viewed as important in the motivation of separate companies to cooperation.

1. Introduction

Norway annually exports around 100 billion Sm³ natural gas, making it one of the largest exporters of natural gas (World Factbook, 2010). Only 1.6% of Norway's natural gas production is used within Norway (Gasco, 2010), with most of the gas delivered to Europe through pipelines. The Norwegian Government has an ambition to increase the value creation from industrial refinement of natural gas, (NRC, 2013). In the national context, Nordland is one of the country's largest export provinces with many mineral-based industries and a good supply of hydroelectric power. Petroleum extraction activities on the Norwegian Continental Shelf are moving northwards, with increasing focus on fields off the coast of Northern Norway, beyond the current extent of the gas pipelines. This gives the potential for added-value processing of local minerals and natural gas.

An annual consumption of natural gas around 2-5 billion Sm³ is assumed in this study to be necessary to justify the landfall of gas in Northern Norway. It is difficult to find a single process that consumes so much gas alone; it would require a combination of different industrial processes. Integration of these industries could give possibilities for synergetic advantages. Thus, a conceptual design of an integrated chemical complex with natural gas and locally sourced minerals as the main raw materials is outlined in this study. The integration emphasizes the unity of the complex and considers the interactions between different plants rather than optimizing them separately. The model can also be used to quantify the individual contribution of each process to the overall result, such that potential benefits and penalties can be

distributed in a fair and transparent manner. This can assist with the motivation of separate companies to cooperation (Dunn and El-Halwagi, 2003)

2. Method

2.1 Study concepts

The Narvik region in Northern Norway has large deposits of pure carbonates, and the ice-free Narvik harbor is used for shipping iron ore from mines in Northern Sweden. Hence a key process is the production of direct reduced iron (DRI) by combining iron ore with natural gas. Further processing of the DRI to steel in a mini-mill would further increase the product value, and could utilize lower grade carbonate from precipitated calcium carbonate (PCC) production. Since the syngas reformer is a major cost contributor to the DRI production it is proposed to use a central synthesis gas plant supplying both the DRI plant, as well as other synthesis gas-based processes such as methanol (MeOH), dimethyl ether (DME), and olefins (propylene or ethylene for plastics, which may also include carbonate filler). The multiple consumers of synthesis gas lower production costs through economy of scale, give flexibility in matching the hydrogen to carbon monoxide ratio, and raise the natural gas consumption to the level required for justifying the landfall of natural gas. The flow of raw materials, products and interactions between the potential processes is shown in Figure 1.

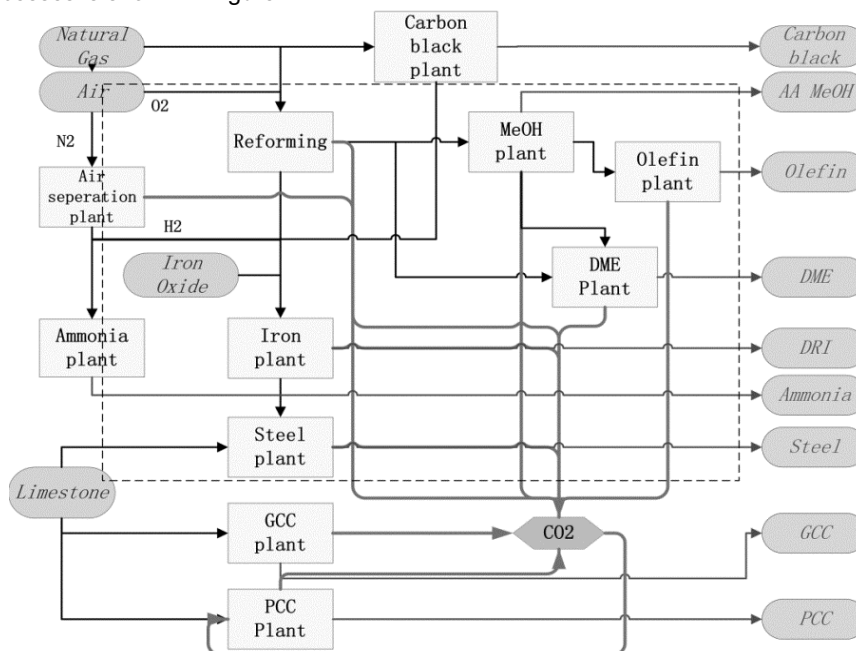


Figure 1: Flow sheet of the potential processes considered for the study

In this study, the initial task is to select potential production processes to be included in the integration, and determine appropriate production rates and amounts of material and heat exchanged between different processes. Exergy analysis, which indicates the quality of energy flows between processes, is included to quantify how efficiently the energy flows are utilized (Elfgren et al, 2010). The direct reduction of iron ore can use hydrogen or carbon monoxide as the reductant. Using hydrogen produces water vapor rather than carbon dioxide, but is an endothermic process requiring additional heating, and the product properties can be affected. Hence there are multiple variables influencing the choice of hydrogen to carbon monoxide ratio. Multi-objective optimization allows the identification of an overall reduction in costs from the relaxation of individual objectives, such as described by Boix et al (2011) for water and energy consumption.

The natural gas is a raw material in these industrial processes that provides both reactants and heat (Liu et al, 2010). Three different methods for converting natural gas into synthesis gas are considered in this project: steam methane reforming (SMR), partial oxide reforming (POX) and autothermal reforming (ATR), each with different ratios of hydrogen (H_2) to carbon monoxide (CO) content. The different downstream processes converting synthesis gas to products have different requirements for the $CO:H_2$ ratio. The selection of the optimal method for producing syngas is influenced by the downstream processes and the efficient utilization of the syngas and heat. Intermediate products like direct reduced iron or methanol can

be exported or processed further to higher value products. All of the proposed processes emit carbon dioxide. The emission of carbon dioxide to the environment would incur emission charges, or a CO₂ capture plant could be incorporated to capture the carbon dioxide from some or all of the processes. Sequestration of carbon dioxide has been investigated with the use of steelmaking slag (Eloneva et al 2012) and magnesium silicates such as olivine (O'Connor et al 2002). There is approximately 6 million tons of finely ground olivine tailings deposited near Narvik which with future research developments might be used to react with CO₂ to form a saleable MgCO₃ product.

Material exchanges between different chemical processes can give direct cost savings for raw materials. In addition there can also be potential savings in transportation and storage costs. There are also challenges that should be addressed while designing the integrated complex. The different processes have different degrees of technical maturity; further developments may be realized in some processes, which in turn could affect the optimal balance of the system. One other important issue within the integrated complex is the dependency between different plants, exposure to unplanned stoppages by connected processes, and the allocation of benefits and liabilities between processes. Development of the model for process design alone is probably not justified, however the model would also find application in optimization of operating conditions in the future. For example the model could be used to identify optimal responses to unplanned stops of individual processes, as production stops create challenges for integrated processes (Walmsley, 2011). The model could be used to make a fair and transparent system for apportioning the benefits (and cost/penalties) arising from process integration of separate processes.

A major impediment to the increased industrial utilization of natural gas is the restriction on carbon dioxide emissions, and this is included as a key component of the optimization. It is necessary to highlight the effect on carbon dioxide emissions in both a local and a global context. Though the amount of carbon dioxide emitted may increase locally due to the industrial cluster, there may be a global reduction due to displacement of more polluting production processes elsewhere, or by greater transport efficiency.

2.2 Objective

Beside utilizing the natural resources in the most efficient and profitable manner, the main objective of this study is to quantify the potential savings in the energy consumption and carbon dioxide emissions for the integrated production processes of the various added-value products. The objective function is expressed as Eq1, and the objective is to minimize it (and hence maximize the profit).

$$\text{Objective} = \sum \text{total costs} - \sum \text{total income} \quad (1)$$

The total income refers to the products and energy sold into the market. The total cost includes capital cost, raw material and energy cost, transportation charge and carbon dioxide tax. The lifetime of the cluster operation is assumed to be 20 years.

The model constructed in this study assists the identification of appropriate scales of production in accordance with the material and energy balances necessary for the economic and market constraints. The material and energy quantities and values of the streams in and out of the processes are also specified. Location specific factors are also included, particularly identifying the advantages and disadvantages and associated cost impacts from the localization in a cold climate region.

2.3 Method of model design

The main methods and the information flows between the various tools are illustrated in Figure 2. The mass and energy flows from raw materials to final products on each plant have been specified with reference to various studies published in the literature. The relationships between variables involved in these flows have been (piece-wise) linearized in a spreadsheet. A mathematical optimization model using the relationships provided from the spreadsheet is then built in an equation editor called reMIND, (Karlsson, 2011) which is based on mixed integer linear programming (MILP). The commercial software CPLEX is then used as the optimization solver for the mathematical model. The optimized results are then returned to the spreadsheet again and the linearized relationships updated if necessary. The sensitivity of the result to various factors and the optima of the system at different scenarios then can be examined. This kind of approach has been used widely in Sweden for optimization studies in the dairy, pulp and paper (Karlsson, 2011) and steel industries (Elfgren et al, 2010).

The interrelationships between the variables make the system non-linear in its response to the variables. A non-linear optimization tool such as GAMS (The General Algebraic Modeling System), (Rosenthal) can be used, but there is the possibility for the solution to find local rather than global optima. Hence the solution of a linearized approximation to the system is useful to confirm the global optimum is found (Lastusilta et al, 2011).

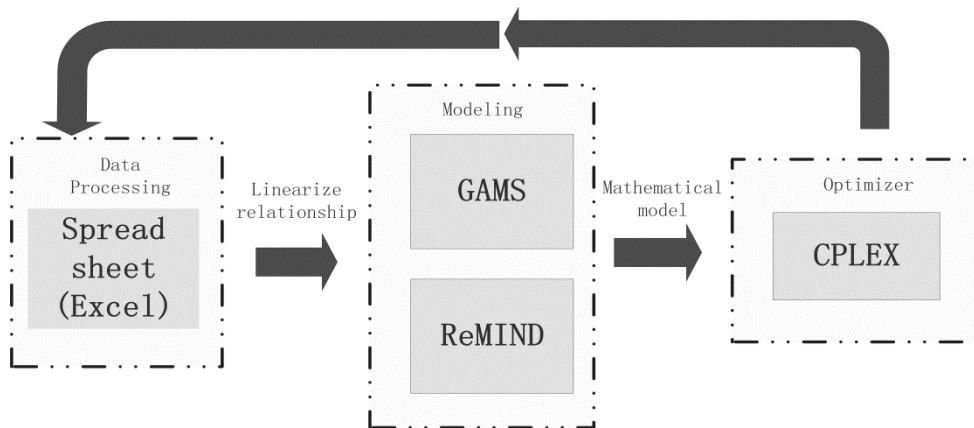


Figure 2: Information flow between optimisation tools used in the study

3. Results

In this part, results from the partially complete model built in reMIND are shown. Processes included in the present model were shown within the dashed line boundary in Figure 1.

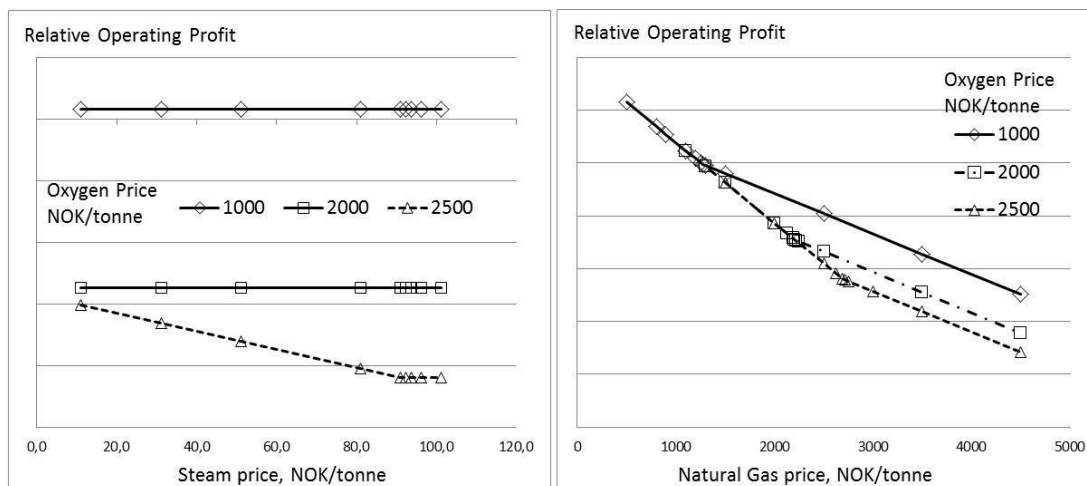


Figure 3: Example of a sensitivity study on two factors a) steam price; b) natural gas price

Sensitivity analyses have been made by judging how the relative profit of the system is affected by different sources of uncertainty in its inputs. All other factors were fixed while examining the sensitivity to one variable at a time. Results of the sensitivity analysis for two representative parameters are shown in Figure 3. When the price of steam changes from 10 to 110 NOK/t, it does not affect the total profit so much especially when the price of oxygen is lower than 2000 NOK/t, Figure 3 a). The model always chose POX as the syngas-producing process when the oxygen price was set at 1000 or 2000 NOK/t. The model only switched to SMR when the price of oxygen increased to 2500 NOK/t and the price of steam was lower than 90 NOK/t. As expected the model was more sensitive to variations in the price of natural gas than to steam, Figure 3b). When the price of natural gas increased to a specific point, the preferred method of reforming switched from SMR to POX. The higher the oxygen price, the later this switch of reforming method happened.

The potential for process integration to reduce the capital costs for the steam methane reforming synthesis gas production process is shown in Figure 4. The relationship between the capital cost and the production was estimated using the exponent method described by equation 2 (Seddon, 2006), using a value of $n = 0.7$.

$$\frac{\text{Capital cost of } p \ 2}{\text{Capital cost of plant 1}} = \left(\frac{\text{Capacity of plant 2}}{\text{Capacity of plant 1}} \right)^n \quad (2)$$

The first bar in Figure 4a gives the sum of capital cost for three separate steam methane reforming plants feeding three individual downstream processes (DME, DRI and olefin). The capital cost for a single syngas process, delivering the summed syngas requirement for the downstream processes, is shown in the second column. The third column represents the capital cost for a single syngas plant feeding the three downstream plants after integration of the processes. In this case the integration has achieved efficiencies due to the balancing of the CO:H₂ ratios. Figure 4b and 4c show equivalent comparisons for the cases with two downstream processes: DRI and DME, DRI and Olefin.

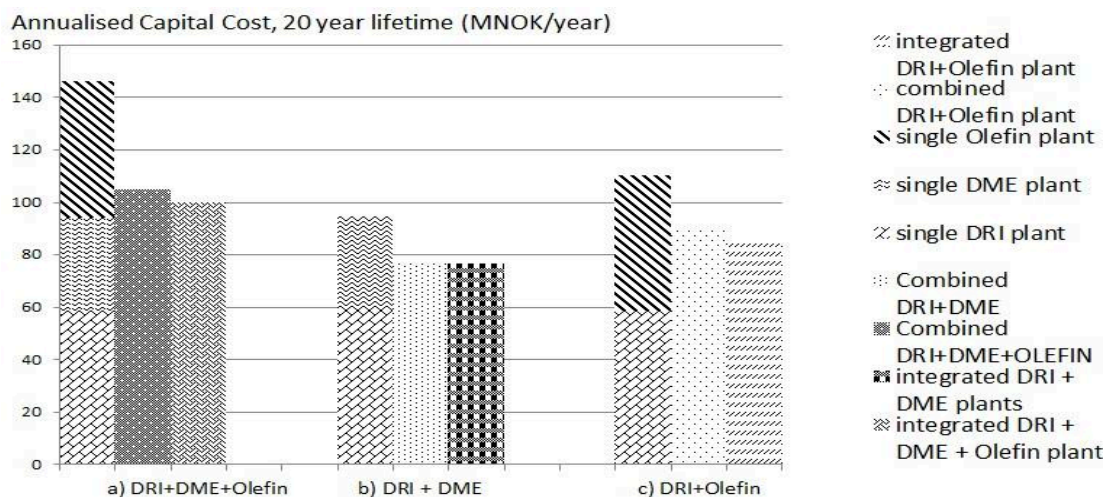


Figure 4: Comparison of annual capital cost for syngas production

When three downstream processes (DRI+DME+Olefin) are supplied by a single syngas plant, the capital cost of the syngas plant is 28 % lower than the sum of the capital costs of three separate syngas plants, Figure 4a. If the ratio of CO: H₂ is adjusted through process integration to meet the individual needs of the downstream processes a further 4 % reduction in capital cost can be achieved. When only two downstream processes were used, the gain from the economy of scale depended on which processes were included. For DRI and DME, Figure 4b, the economy of scale saving of a central syngas plant was about 21 %, while for DRI and olefin, Figure 4c, it was about 19 %. There was no gain from the process integration optimization for the case of DRI+DME (Figure 4b) mainly because both processes consume syngas with a lower CO:H₂ ratio than produced by SMR. However, since DRI and olefin have CO:H₂ ratios respectively lower and higher than that produced by SMR, greater gains from process integration were obtained. The additional capital cost saving from process integration of the DRI and olefin case, Figure 4c, were about 5 %, which is in line with the syngas production capacity savings as per equation 2. These syngas plant capital cost results were obtained from a process integration optimization of CO₂ tax and product value while allowing hydrogen to be separated and exchanged between processes. Additional gains are expected as other variables are included (heat, other capital costs, operational cost, etc.)

4. Discussion

Although the model involves numerous approximations and simplifications the results show it is able to identify which variables have significant impacts on the optimization, allowing further attention to be paid to these. The identification of the most important variables is also important for risk management of the system. Critical variables with a large impact on the optimal performance should have contingency plans in place. Other variables may be able to be compensated for by adjusting the system, in which case they are less critical. This analysis can form part of a fair and transparent system for apportioning the benefits and penalties arising from the integration. This can assist in motivating the different companies to collaboration. Savings in the capital cost are identified from both economies of scale, as well as more efficient utilization of the resources. Downstream processes with different requirements for the ratio of carbon monoxide to hydrogen can be balanced in an integrated system, improving the resource utilization. Changes in the types and capacities of the downstream syngas processes affect the choice of the optimal reforming method, since the different syngas processes have different syngas compositions in terms of carbon monoxide to hydrogen ratio.

5. Conclusions

The model showed the ability to balance interacting and conflicting demands such as capacity, raw material prices and product compositions. Sensitivity analysis allows the critical variables to be identified, and more attention paid to improving the description of these. The optimization indicates which changes can be adapted for by re-optimization, and which will have significant impacts despite re-optimization. In this way the model can be used for the optimization of both the design process, as well as the operating mode. In the event of process disturbances, such as unplanned production stops or unavailability of raw materials, the model can be used to identify adjustments to achieve a revised optimum performance. This also allows the quantification of the contribution of the different processes to the overall result in a fair, transparent and quantitative manner.

Further development of the model will include the costs of carbon dioxide emissions and transport. Synergies may be realized through integrating delivery of raw materials and products for different processes. It is also necessary to analyze the production capacity in terms of market capacity, location and transport arrangements.

Acknowledgements

This study is supported by Nordland fylkeskommune (Provincial Government); Luossavaara-Kiirunavaara AB, BP Norge, Northern Research Institute Narvik A.S. and the Norwegian Research Council project number 195153. Useful discussions with the staff of Swerea MEFOS are also acknowledged.

References

- Boix M., Montastruc L., Pibouleau I., Azzaro-Pantel C., Domenech S., 2011, Minimizing Water and Energy Consumptions in Industrial Water Networks, *Chemical Engineering Transactions*, 24, 307-312.
- Dunn R., El-Halwagi M.M., 2003, Review: Process integration review: background and applications in the chemical process industry, *Journal of Chemical Technology and Biotechnology*, 78, 1011-1021.
- Eloneva S. Said A., Fogelholm C.-J., Zevenhoven R., 2012, Preliminary assessment of a method utilising carbon dioxide and steelmaking slags to produce precipitated calcium carbonate, *Applied Energy*, 90, 329-334.
- Elfgrén E., Grip C.E., Wang C., Karlsson J., 2010, Possibility to combine exergy with other process integration methods for a steelmaking case, *Chemical Engineering Transaction*, 21, 1375-1380.
- Feinman J., Rae D.R.M., 1999, *Direct Reduced Iron: Technology and Economics of Production & Use*, Iron & Steel Society, Warrendale, PA, USA
- Gassco, 2012, Facts 2012: Gas export from the Norwegian shelf, <www.npd.no/Templates/OD/Article.aspx?id=4312&epslanguage=en> accessed 21.03.2013.
- Karlsson M., 2011, The MIND method: A decision support for optimization of industrial energy systems – Principles and case studies, *Applied Energy*, 88, 577 - 589
- Liu K., Song C.S., Subramani V., 2010, *Hydrogen and Syngas Production and Purification Technologies*, John Wiley & Sons, USA.
- NRC, 2013, Norwegian Research Council, Gassmaks research programme, <www.forskningsradet.no/prognett-gassmaks/Home_page/1228296770594> accessed 20.02.2013.
- O'Connor W.K., Dahlin D.C., Rush G.E., Dahlin C.L., Collins W.K., 2002, Carbon dioxide sequestration by direct mineral carbonation: process mineralogy of feed and products, *Minerals and Metallurgical Processing*, 19, 2, 95-101
- Rosenthal R.E., A GAMS Tutorial, <www.gams.com/dd/docs/gams/Tutorial.pdf> accessed 20.02.2013
- Seddon D., 2006, *Gas usage and value: the technology and economics of natural gas use in the process industries*, Penn Well Corporation, USA.
- Lastusilta T, Papageorgious L.G., Westerlund T., 2011, A comparative study of solving the problem of module identification in a complex network, *Chemical Engineering Transaction*, 24, 319-324.
- Walmsley M.R.W., Atkins M.J., Morrison A.S., Neale J.R., 2011, Importance of understanding variable and transient energy demand in large multi-product industrial plants for process integration, *Chemical Engineering Transactions*, 25, 381-386
- World Factbook, Central Intelligence Agency, 2010, Country comparison: Natural gas exports <www.cia.gov/library/publications/the-world-factbook/rankorder/2183rank.html> accessed 21.03.2013.