GAS BASED INDUSTRIAL CLUSTER FOR PRODUCTION OF DRI, STEEL, METHANOL AND CARBON BLACK; THE TECHNICAL AND ECONOMIC EFFECTS OF NATURAL GAS WITH HIGH CO_2 CONTENT[1]

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Abstract

In this paper the economic and technical effects of using CO_2 rich natural gas in an industrial cluster are analyzed. The basis for the work is a technical-economic description the processes in the different plants. A mathematical model is established that enable analysis and optimization of design and operation of the industrial cluster. The model maximizes the net present value of the available investment possibilities and optimizes the resulting operational opportunities. The candidate plants considered in this case study are; a DRI plant, a steel plant (EAF), a methanol plant, a carbon black plant, a combined cycle power plant and a carbon capture facility. Norway is used as a case study region due to the political ambitions of increasing domestic use of natural gas to achieve a higher level of innovation and industrial development. Several scenarios are analyzed, and the main findings from this case study are that there could be both environmental and economic benefits by using a CO_2 rich gas (typical 8%-10% CO_2) in an integrated industrial cluster.

Key words: Industrial cluster; DRI (direct reduced iron); Steelmaking; Methanol.

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1 INTRODUCTION

Natural gas production is an important part of the Norwegian petroleum industry and the Norwegian economy. In 2010 it accounted for almost a quarter of the total GDPs and half of the exports according to the Norwegian Petroleum Directorate (NPD).(1) Both in a European context and on a world scale, the Norwegian gas production is considerable with Norway being the second largest gas exporter in the world and Norwegian natural gas accounting for almost 20% of total European gas consumption. However, domestic consumption of natural gas is only 1.6% of total Norwegian gas production.(1) Norway has an economic policy regarding natural gas aiming at increasing domestic use of natural gas, both in connection to existing landing terminals, and also potential new landing places for gas as described in a White Paper in 2003.(2) The main motivation for increasing the national industrial use of natural gas is to get a higher level of innovation and development of new industries related to natural gas. The location of the natural gas fields as well as other natural resources such as iron ore are located in areas in Norway with limited employment options – this strengthens the political motivation for establishing such industrial clusters. Other factors have also made the utilization of natural gas more interesting: the liberalization of the power markets has lead to a shortage of power (and high prices) in some areas in Norway during winter; and new small fields have been discovered off the coast of Norway. For these new fields there is currently no available infrastructure to transport this gas to the gas markets in Europe. One alternative solution for development of these fields is to bring the gas onshore for industrial use. Such a use of the gas can facilitate the development of new technologies to allow efficient and cost-effective monetization of these small assets. Industrial utilization of natural gas is often associated with stranded gas fields where there are limited or no possibility to directly export the gas to a market. This may arise in situations where distances to the markets are long, the fields are small or the natural gas does not meet demand or pipeline specifications with respect to gas quality (for instance due to a high content of CO_2). To resolve this latter problem, the gas must normally be processed before being transported and sold. In some instances it can also be possible to blend the natural gas with higher quality gas (if fields with such gas are available). In such situations it is particularly interesting to consider the possibilities of industrial utilization in, for instance, integrated materials (and chemicals) producing industrial clusters. In Norway there can be a trade-off between processing the natural gas with high CO_2 content to meet the quality demand from the European customers and utilizing the gas directly in industrial process that can handle high CO_2 content.

The study presented here is part of the GassMat project (Norwegian Research Council project number 187465), which has its basis in the ambition to increase the domestic use of natural gas in Norway. Several industrial partners, such as Statoil, Celsa Group, LKAB, Alstom, Sydvaranger Gruve and Fesil Sunergy, have been participating in the project. The goal of the project is to establish a methodology for technical, environmental, and economical analysis of a natural gas based integrated industrial cluster. In the case study presented in this paper the industrial cluster consists of a combined cycle power plant, a direct reduced iron (DRI) plant, a steel plant, a methanol plant and a carbon black plant. The natural gas is an important input factor to these processes both for power production and as raw material in industrial processes that produce materials and heat. All the processes in the cluster emit CO_2, but the concentration of the CO_2 in the exhaust gas (and the amount of it) differs for the different plants. The CO_2 can be emitted to air, where it may be subjected to CO_2 taxes (equivalent to the price of CO_2 quotas), or a carbon capture plant designed for flexible operation can be installed to capture the CO_2 from some or all of the processes.

An integrated industrial cluster consists of a number of plants with different characteristics that produce different products and by-products. One of the benefits of industrial clusters is that by-products, which are not technically or economically suitable for long distance transport, can be exchanged within the cluster. In addition there are economies of scale present due to for instance shared assets and resources. Between the plants there will also be a potential for savings in transportation and inventory costs, and additionally, the environmental costs can be reduced. However, the industrial cluster perspective also strengthens the importance of flexible operation for the individual plants. When prices, demand or supply of raw materials change it may be necessary to also adjust production in one or more plants. This poses a challenge for the coordination in the cluster and can also require that one or more plants are operated off-design. The varying production levels in the plants in the industrial clusters make it important for a carbon capture plant to be able to handle such variations, and operate as efficiently as possible. The industrial cluster considered in this paper is illustrated in Figure 1.

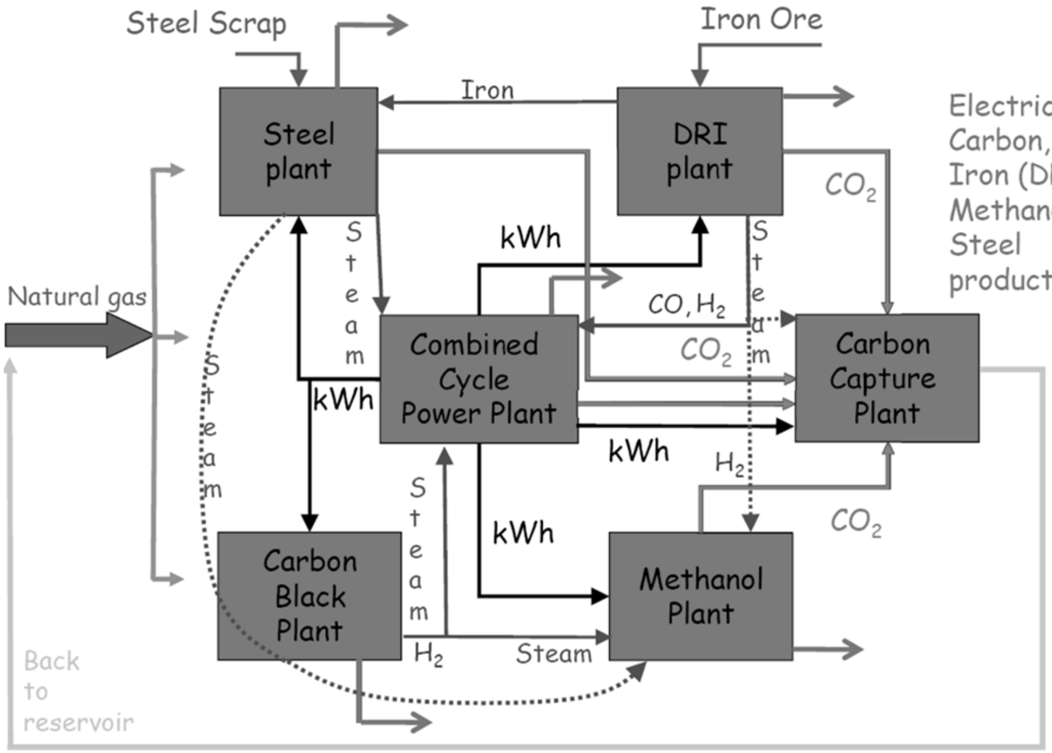


Figure 1. An illustration of the industrial cluster considered including potential plants as well as the flow of products between the plants and to the market. Natural gas is available for all 6 plants in the industrial cluster, but is generally not used in the Carbon Capture Plant.

The main contribution of this paper is an analysis of the economic and technical effects of using CO_2 rich natural gas in an industrial cluster. This is illustrated by considering a case study where an analysis of how gas with a high CO_2 content will affect the optimum investment, operation and configuration of the industrial cluster. A system perspective is used in the analysis, meaning that one central planner is assumed to make all decisions in the industrial cluster. This gives a benchmark

solution which is the highest achievable total net present value in the cluster. The coordination mechanisms used to align the decision makers in the industrial cluster will then decide how close to this benchmark solution the cluster will come. These considerations are however out of the scope for this present analysis.
After presentation of the methodology and main assumptions used in the analysis a discussion of how the different plants included in the case study can handle natural gas with high CO_2 content is provided. A description of the case study and scenarios is given followed by the results from the computations and concluding remarks.

2 METHODOLOGY AND ASSUMPTIONS

This analysis of high CO_2 gas in an industrial cluster is based on process simulation, economical calculations, and statistics as well as optimization tools.

2.1 Process Simulations and Estimation of Production Functions

Technical process simulations are performed for all processes in the cluster with suitable simulation tools (Metsim (v. 16.06, Proware), GTPro (v. 2008, Thermoflow Inc.), Hysys (v. 2006.5, AspenTech) and ProTreat (v. 3.10, Optimized Gas Treating, Inc). The simulation tools can handle non-convex relationships between the variables. However, even these tools have limitations with respect to representing the real production processes. The results from the simulation tools are therefore discussed with industrial partners in the GassMat project. Simulation results are combined with experience process data and statistical analysis performed to estimate production functions relate input and output variables for the processes within each plant in the cluster. Based on these relationships a mixed integer linear programming model is formulated and implemented in Xpress-MP (v. 2008a, Fico). The programming model offer flexibility regarding both the design of and the operation of the individual plants and the possible connections between the different plants. Thus optimisation yields design and operation of the plants in a way that that take care of the integrated cluster concept. For details regarding the optimization model, see Midthun et al.(3) For validation, optimisation results are finally simulated and discussed with the relevant technical expertise.

2.2 Maximization of Net Present Value

The objective of the developed optimisation model is to optimise investment and operation of the cluster for a given case and scenario, which implies maximisation of net present value (NPV), defined as the present value of the cash flow (*PVcf*) minus the present value of investments (*PVinv*). Cash flow (*CFP,t*) include revenue from products and energy sold in the markets, costs of raw materials, operation costs, and CO_2 and NOx tax payments. Present value of investments comprises investments *Ip* in different plants or units (*p*) that together make up the cluster. The objective function in the model is then:

$$NPV = PV_{cf} - PV_{inv} = \sum_{p \in P} \sum_{t \in T} \frac{1}{(1+r)^{t-1}} \cdot CF_{P,t} \cdot (1-s) - \sum_{p \in P} I_p \left[1 - s \cdot \gamma \cdot \frac{1+r}{r+\gamma} \right] \qquad (1)$$

Where *s* is the tax rate, © is the deprecation rate used for reducing balance, and *r* is the real required rate of return after tax. The set *P* represents all investment opportunities i.e. all plants, equipment and internal infrastructure units and the set *T*

represents all time periods in the model. For the cases/scenarios the time horizon of the cluster operation is assumed to be 20 years.

It is assumed that all investments are done simultaneously at time period 0 (before the operation of the cluster begins). Accordingly investments are not discounted as they accrue at time period 0 which is equivalent to present time. The standard assumption that the particular company or companies always will be in a tax-paying position (either from the operation in the cluster or due to other businesses) is used throughout. This yield a simple adjustment for tax deductions due to depreciation of assets, see second term in the rightmost bracket of Equation 1. The investment modeling includes a set of discrete investment possibilities for each plant, implemented by binary variables that indicate whether or not a plant is selected (these binary variables also take care of some additional design flexibility at sub-plant level). Linked to the binary variables, continuous variables are used to model capacity. In total, the investment cost, I_p, for each plant consist of a fixed part and a variable part that depends on the installed capacity. As a result of unanticipated changes during the analysis horizon, installed capacity might be higher than production level in a given time period, allowing periods of off-design operation. The operational costs are dependent on both the total installed capacity and on the actual production in the plant in each time period.

2.3 Pricing of Lower Quality Gas

Natural gas with high CO_2 content has a lower heating value than the typical Norwegian gas and is considered to be of lower quality. Table 1 shows the main differences in gas properties between the lower quality CO_2 rich gas and a typical gas from the Norwegian Continental Shelf (NCS). Both these gas compositions are used in the analysis.

Table 1 Properties of the two different gas compositions used

Gas property	***Original NCS***	***CO_2 rich***
CO_2-content	1.6%	8.6%
Higher hydrocarbons (C2+)	9.7%	3.5%
Molecular mass, kg/kmol	18.8	19.2
Lower heating value, kJ/kg	47038	39836

There are different ways to adjust the price charged for the natural gas with lower quality. The main differences between the typical gas from the NCS and the low quality gas are lower heating value and higher CO_2 content. Both these aspects can give price reductions compared to the price charged for natural gas in the markets in Europe. This corresponds to adjusting the price of natural gas to reflect the disadvantages and burdens that the lower quality gives. Two price adjustments are considered in this study. The first approach is to adjust the price in accordance with the ratio between the Gross Calorific Values (GCV) of the two gas compositions (Equation 2).

$$\mathrm{Price}_{high\ CO_2} = \frac{GCV_{high\ CO_2}}{GCV_{normal}} \cdot \mathrm{Price}_{normal} \qquad (2)$$

The second approach is based on adjusting the gas price for the increase in CO_2 content. This applies when taxes are charged for CO_2 emissions when the gas is burnt. In addition, the high concentration of CO_2 may be a problem for some processes and equipment. As seen from Table 1, one kg of CO_2 rich gas with 8.6 volume-% CO_2 contains 0,196 kg CO_2, while 1 kg of the typical Norwegian gas (1,6% CO_2) contains 0,037 kg CO_2. To adjust the price to account for the increased CO_2 content burden the price of the additional CO_2 is subtracted in accordance with the assumed carbon tax level.

$$\text{Price}_{high\ CO_2} = \frac{GCV_{high\ CO_2}}{GCV_{normal}} \cdot \text{Price}_{normal} - (0.196 - 0.037) \cdot carbon\ tax \qquad (3)$$

The result of these price adjustments are shown in Figure 2 for each year of the time horizon.

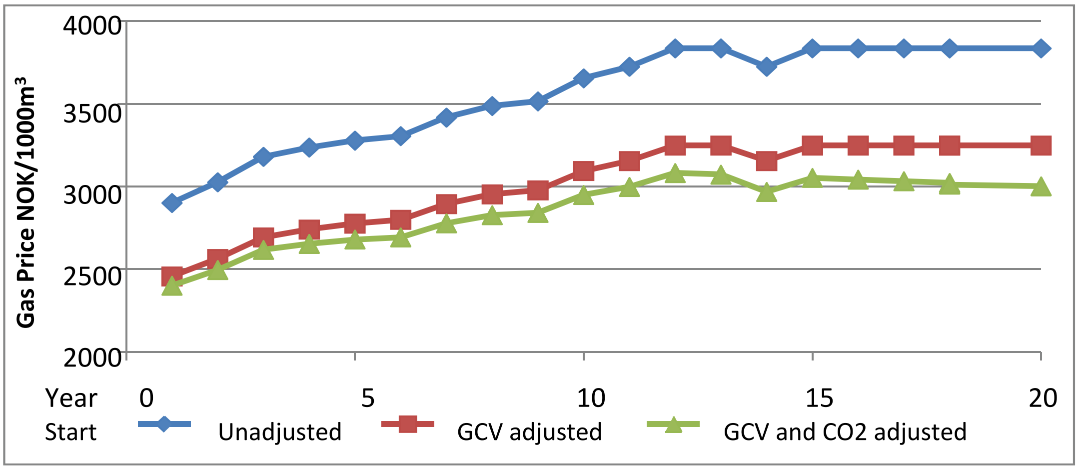


Figure 2. Development of the natural gas price per 1000 cubic meter given in Norwegian Kroner (1 USD ~ 6 NOK) based on 2010 as project start. The *unadjusted* natural gas price is the price paid for the original gas. This price forms the basis for the calculations of net present value denoted by NPV1. The GCV (gross calorific value) adjusted gas price (Eq. 2), and the price adjusted for both GCV and CO_2 content (Eq. 3) form the basis for the calculations of net present values NPV2 and NPV3 respectively. Note that only the price for the gas with a high CO_2 content is adjusted.

3 MODELLING OF THE INDIVIDUAL PLANTS FOR HIGH CO_2 CONTENT

In this section the effect for the individual plants of using a natural gas feed with CO_2 levels substantially above export specification is outlined before the analysis of the plants' and cluster's joint ability to make profitable use of such CO_2 rich gas is presented. The units outlined are an iron making plant, a steel plant, a carbon black plant, a methanol plant and a combined cycle power plant.

3.1 DRI

In the metallurgical industry the most pronounced use of Natural Gas is for the reduction of iron oxides to produce Direct Reduced Iron (DRI), and this has naturally been of interest for research communities in Norway(4-6) for many years. Production of iron carbide(7) and conversion of Natural Gas to Syn Gas(8) are related activities that also have been studied. The Norwegian metallurgical industry and research institutes have for many years argued that such processes represent a viable option for export of processed gas.(9)

The DRI plant can handle CO_2 rich gas very well. However, the natural gas consumption to produce the same amount of DRI increases, and so do the CO_2

emissions but also the steam production. The CO_2 richer gas has a lower heating value, and natural gas consumption increases in accordance with the heating value ratio. CO_2 output is increased with the amount of CO_2 going in. The natural gas is used for both heating and for reforming. The reforming gas loops around, and is heated by the heating gas in the reformer burner. So in the burner, more gas is needed to supply the same amount of heat. Figure 3 shows the flow sheet of the DRI plant showing the substantial integration of heat and mass flows and interchange. Similar integration also exists in the methanol and carbon black plants.

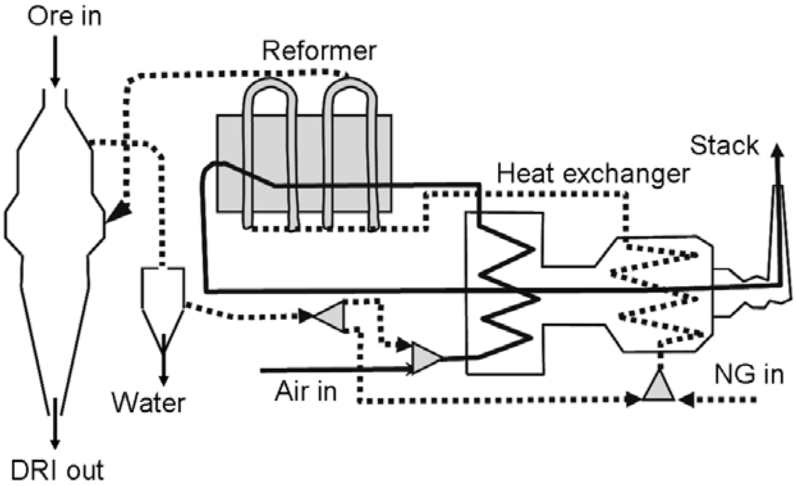


Figure 3. DRI plant main units illustrating integration between reduction gas (stippled lines) and combustion gas (full lines). The reduction (CO+H2) gas is produced in the reformer and enters the reduction shaft to the left of the figure. The shaft exit gas is dewatered by quenching and is then split into two flows. One of these flows is mixed with air and reheated in the heat exchanger before combustion to provide heat for the reformer and then the combustion gas is passing through the heat exchanger on the hot side before finally exiting through the smoke stack. The second flow is mixed with natural gas, and the mixture is preheated before entering the reformer on the catalyst side for the production of new reduction gas according to $CH_4+CO_2=2CO+2H2$.

In the reforming loop, more gas is required to reduce the iron ore, since CO_2 inhibits the reaction. So, more gas goes through the loop that needs more heat, at the same time as the gas itself has lower heating value. However, the greater amount of gas circulating gives more heat that can be exchanged with steam production. This gives more steam from the heat exchangers with the top gas, and especially more HP (high pressure) steam. The steam is used to produce power in a steam turbine.

3.2 Steel

In the steel plant, natural gas can to an extent be a substitute for electricity, and there is an upper limit on how much natural gas that can be used in the steel production. Lower quality gas will increase the amount of natural gas required if natural gas is used in the same manner as for power production. Oxy-fuel burners and oxygen lances may also be used to supply chemical energy. Oxy-fuel burners, which burn natural gas and oxygen, use convection and flame radiation to transfer heat to the scrap metal.

According to a recent report from the United States Environmental Protection Agency (EPA),(10) oxy-fuel burners are used on approximately half the EAFs in the U.S. These burners increase the effective capacity of the furnace by increasing the speed of the melt and reducing the consumption of electricity and electrode material, which reduces GHG emissions. The use of oxy-fuels burners has several beneficial effects: it increases heat transfer, reduces heat losses, reduces electrode consumption and, and reduces tap-to-tap time. Moreover, the injection of oxygen helps to remove different elements from the steel bath, like phosphorus, silicon and carbon. Steelmakers are now making wide use of stationary wall-mounted oxygen-gas burners and combination lance-burners, which operate in a burner mode during the initial part of the melting period. When a liquid bath is formed, the burners change over to a mode in which they act as oxygen lances. Natural gas injection is typically 300 m^3/MWh, with energy savings ranging from 20-40 kWh/tonne. Investment cost for modifying a 110 tonne EAF was estimated to be $7.5/tonne.

3.3 Methanol

Modeling of the methanol production is based on two-step reforming of natural gas. In the reforming section, heat and oxygen are added, and the hydro-carbons in the natural gas are broken down into hydrogen (H_2) and carbon monoxide (CO). Then, in a synthesis section, methanol can be formed by $2H_2 + CO = CH_3OH$ or by $CO_2 + 3H_2 = CH_3OH + H_2O$. Accordingly, increased CO_2 content in the gas feedstock can be used to make larger amounts of methanol, as long as the hydrogen content of the gas is sufficient. In these cases, this requires more H_2 and therefore a higher volume of natural gas (hydrocarbons) is needed to feed the plant (as long as the H_2 has to be produced in the methanol plant itself and not supplied from another plant). Remark that a significant part of the H_2 produced is used for energy production in the methanol plant. In total, this results in an increased natural gas consumption to produce the same amount of methanol on a stand-alone basis for the methanol plant. The increase is in line with the relative difference of heating value. The O_2 consumption in the production, and the exhaust and CO_2 emitted, however, decreases.

Similar results are also shown in Aasberg-Petersen et al.(11) They describe a one-step reforming process, where the CO_2 volume in the natural gas is significant. The synthesis gas produced by one-step reforming will typically contain a surplus of hydrogen of about 40%. The addition of CO_2 in the feedstock permits optimisation of the synthesis gas composition for methanol production, and CO_2 emission to the environment is reduced. Furthermore, Aasberg-Petersen et al. (2008) state that gas that is rich on CO_2 often constitutes a less expensive feedstock, and they conclude that the application of CO_2 reforming results in a very energy efficient plant. The energy consumption is 5–10% less than that of a conventional plant.

3.4 Carbon Black

CO_2 rich gas can be handled well in the carbon black plant too. Producing the same amount of carbon black will require increased use of natural gas when the CO_2 volume is higher. The increase is relatively higher than the difference in heating value relation. In the process the hydrocarbons in the feed are transformed into H_2 and C (Carbon Clack). The CO_2 reacts with some of the carbon and is transformed into CO. Hence, raising the level CO_2 in the feedstock, more of the carbon – the product - is consumed in the process. Thus, to maintain carbon production at a given level, more gas has to be supplied and accordingly more CO and H_2 will be produced. The additional amount of synthesis gas can be used to produce power in a gas turbine or heat in the methanol plant.

3.5 Power Plant

The turbines in the power plant model can handle gas with CO_2 content up to 10%. Heating value of CO_2 equals zero so utilizing gas with high CO_2 content leads to increased consumption of natural gas to produce the same amount of power, as the power production is a function of fuel energy input related to the heating value. In addition, this will result in increased CO_2 emissions as the additional CO_2 will simply go straight through the turbines.

4 CASE SETUP AND SCENARIOS

4.1 The Case

The candidate plants for the industrial cluster case study consist of an iron plant, a steel plant, a combined cycle power plant, a carbon black plant, a methanol plant and a carbon capture plant as described earlier. Figure 1 illustrates the flow of the most important raw materials and finished products in the cluster. In addition, the figure also shows the possible interactions between the lants. For instance, the combined cycle power plant can use natural gas, synthesis gas and steam to produce electricity. The electricity may either be used by the plants in the cluster or sold in the electricity market. The synthesis gas input comes from the DRI plant, and the steam can come from several plants in the cluster. The exhaust gas from the power plant may then be sent to a carbon capture facility to reduce the emissions of CO_2.

In this cluster, the DRI, steel, methanol and power plant emit CO_2. The off gas CO_2 concentrations from the different plants varies between 3% - 19%. The exact numbers depend on how the plants are operated regarding production level, use of by-products from other plants (such as synthesis gas containing H2 and CO), and the natural gas input. For instance, the DRI plant can produce excess synthesis gas that mainly consists of H_2, CO and CO_2 and send this to the power plant. This results in lower CO_2 concentrations in the exhaust gas from the DRI plant. However, the exhaust from the gas turbine running on this synthesis gas will have higher CO_2 concentrations.

4.2 Main Assumptions and Scenarios

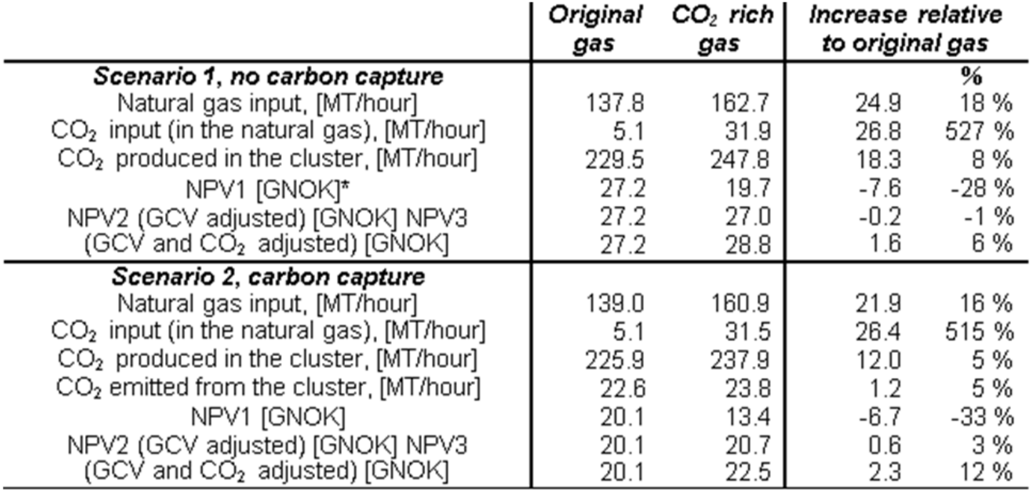
Optimum investment in the industrial cluster will depend upon several different parameters, such as investment cost, operation cost, and cost of raw materials and prices of produced products. In the following section the main assumptions related to this case, as well as the basis for the modeling of carbon capture investment and operations are presented.

All the candidate plants in the cluster (except for the carbon capture plant) use natural gas as raw material. In the case study a time horizon of 20 years is used. Forecast values for the prices 20 years ahead in time are based on a prognosis made by the Norwegian Petroleum Directorate.(12) The time profiles of the CO_2 taxes and the electricity price are based on a prognosis made by Statistics Norway.(13) The prognosis assumes ambitious climate politics in EU towards 2020, but which stagnates towards 2030. EU's target is to reduce emission of greenhouse gases by 20% within 2020, planning to charge higher prices on emissions on CO_2. The main setting of the prognosis is chosen in cooperation with the Climate and Pollution Agency. The predicted values that are used in the analysis are shown in Figure 2 for natural gas; similar relationships are used for CO2 taxes and electricity. The historical relationships between the natural gas price and the price of raw materials and products have also been studied. These relationships have then been used to predict how the prices for the different materials will develop (the ratios to the natural gas price are assumed constant in the optimization horizon).

5 RESULTS AND DISCUSSION

Results for two different scenarios; 1 and 2: Scenario 1 - Only the power plant has to pay CO_2 taxes; and In Scenario 2 - All plants have to pay CO_2 taxes are presented. For each scenario the results from using the original gas with a low CO_2 level is compared with the results from using the CO_2 rich gas. Furthermore, for the analysis with the CO_2 rich gas, the results from using the three different pricing alternatives presented earlier are also presented. The price for the original gas is the same in all calculations, while the price for the gas with a high CO_2 content is adjusted. The resulting prices are shown in Table 2. The Net Present Value (NPV1) by using the unadjusted price for both gas alternatives, as well as the net present value from using the gas with a high CO_2 content with price adjustments (NPV2 and NPV3) for both scenarios are then found. An overview of the results is provided in Table 2, while the next subsections will give a closer discussion of these results.

Table 2 Overview of the results from the analysis of the two different scenarios and the two different gas compositions. The net present value (NPV) is given in billions of Norwegian Kroner (GNOK). The abbreviation GCV stands for gross calorific value



	Original gas	*CO_2 rich gas*	*Increase relative to original gas*	
Scenario 1, no carbon capture				**%**
Natural gas input, [MT/hour]	137.8	162.7	24.9	18 %
CO_2 input (in the natural gas), [MT/hour]	5.1	31.9	26.8	527 %
CO_2 produced in the cluster, [MT/hour]	229.5	247.8	18.3	8 %
NPV1 [GNOK]*	27.2	19.7	-7.6	-28 %
NPV2 (GCV adjusted) [GNOK] NPV3	27.2	27.0	-0.2	-1 %
(GCV and CO_2 adjusted) [GNOK]	27.2	28.8	1.6	6 %
Scenario 2, carbon capture				
Natural gas input, [MT/hour]	139.0	160.9	21.9	16 %
CO_2 input (in the natural gas), [MT/hour]	5.1	31.5	26.4	515 %
CO_2 produced in the cluster, [MT/hour]	225.9	237.9	12.0	5 %
CO_2 emitted from the cluster, [MT/hour]	22.6	23.8	1.2	5 %
NPV1 [GNOK]	20.1	13.4	-6.7	-33 %
NPV2 (GCV adjusted) [GNOK] NPV3	20.1	20.7	0.6	3 %
(GCV and CO_2 adjusted) [GNOK]	20.1	22.5	2.3	12 %

**GNOK = Billions of NOK = 109 NOK (1 USD ~ 6 NOK)*

5.1 Emission Results

When the industrial cluster is supplied with the natural gas with high CO_2 content, the natural gas consumption increases with 16 to 18% compared with the cases with the original gas composition. Correspondingly, the CO_2 input is about five times higher in the CO_2 rich cases. This also results in increased CO_2 produced in the cluster. However, the increase of 5 – 8% is much smaller than the additional input (also in absolute terms – see Table 2). The figures show that when the CO_2 input is increased with 26.4 tons per hour in scenario 2, the additional CO_2 production in the cluster is only 12.0 tons per hour (for scenario 1 the corresponding figures are 26.8 and 18.3). There are several reasons for this result. One reason is that the additional CO_2 in the gas feedstock to the methanol plant carries over to the product contributing to a higher methanol production. Also the steam production in the DRI plant is higher, resulting in a higher power production in the combined power plant's steam turbine, and correspondingly a lower power production and fuel input in the gas turbine. In addition, the carbon black plant and the DRI plant produces some more synthesis gas.

5.2 Investment Results

In scenario 1, where only the power plant is subject to a CO_2 tax, it is optimal not to build a carbon capture plant. In this situation, it is more cost efficient to pay taxes for the CO_2 emitted from the power plant than to build and operate a carbon capture plant. This result is independent of whether original or CO_2 rich gas is used. In scenario 2, where all the plants are subject to CO_2 taxing, the optimum cluster configuration includes a carbon capture plant. In this situation, the carbon capture plant is used to capture CO_2 from all the plants. In addition, the carbon black plant has also become profitable in scenario 2. The carbon black plant produces steam which can be utilized in the methanol plant. This additional supply of steam decrease the emissions of CO_2 from the methanol plant since the steam substitute heat generated in the methanol plant itself and hence yield reduced natural gas consumption. In addition, when a carbon capture plant is installed, synthesis gas flows from DRI to a gas turbine in the power plant. The synthesis gas turbine will then also utilize the synthesis gas from the carbon black plant.

5.3 Economic Effects

In this subsection the three different gas pricing alternatives for the CO_2 rich gas and their influence on the economic analysis results are compared. When the gas price for the two cases with different gas composition is equal, the net present value (NPV) for the industrial cluster when using the CO_2 rich gas decreases with approximately 30%. The configuration of the cluster, however, remains equal, and the cluster is profitable both with the original gas and the CO_2 rich gas.

When the natural gas price is adjusted in accordance with the ratio between the heating values the resulting net present value when using the CO_2 rich gas significantly increases for scenario 1. The net present value is now only 1% lower than the result with the original gas. In scenario 2 this price adjustment increases the net present value to a level that is 3% higher than the net present value from using the original gas composition. This illustrates that the carbon capture is more efficient when the input gas has a high CO_2 concentration.

The natural gas price is then also adjusted for its CO_2 content directly by compensating for the CO_2 tax (i.e. carbon quota price). In this alternative the net present value (NPV3) is higher in the CO_2 rich gas cases for both scenarios. The difference between the net present value from the high CO_2 gas analysis and the original gas analysis is, respectively, 6 and 12%.

The changes in net present value between cases using original gas and CO_2 rich gas are due to several effects. Firstly, when the natural gas price is not adjusted, the large decrease in the net present value is mainly caused by the higher costs of buying lower quality natural gas (16-18% more gas). Secondly, when a carbon capture facility is built, the investment and operation costs of this facility is 1-3% higher for the rich CO_2 gas cases, because of the increased total amount of CO_2 that is captured. The amine usage and costs are correspondingly also higher. When a carbon capture facility is not built, then the total CO_2 taxes are approximately 7% higher when using the CO_2 rich gas. On the other hand, the CO_2 rich gas results in higher steam production and also higher production of synthesis gas, utilized in the power plant. In that way, more power is produced and sold in the market.

These results show both environmental and economic benefits by using the CO_2 rich gas. The additional CO_2 emissions for the CO_2 rich gas case is not as high as the additional input, and in the case where a carbon capture plant is installed, the final quantity of CO_2 emitted from the cluster is found be almost invariant with respect to the level of CO_2 in the gas supplied. By adjusting the gas price for the disadvantages with CO_2 rich gas (lower heating value and "compensation" for increased carbon taxes), the net present value for the cluster will be higher for the same end products produced. This could make it sustainable both environmentally and economically to use CO_2 rich gas in material (and chemicals) producing industries.

6 CONCLUSIONS

In this study a decision support model for an integrated industrial cluster is presented. The cluster consists mainly of materials producing plants that use natural gas as raw material. Based on maximization of net present value, the model finds optimal design of the industrial cluster as well as optimal operation of the installed equipment over a given time horizon.

Given the increased focus on CO_2 emissions, such as discussions regarding mandatory carbon capture and emission taxes, the possibility of utilizing CO_2 rich natural gas in such industrial clusters are explored. The motivation for such studies is further strengthened by exploration of smaller gas fields on the Norwegian Continental Shelf, or elsewhere, which may contain high levels of CO_2. The CO_2 rich gas poses challenges both for transportation (due to restrictions on content in gas pipes not designed for high CO_2 levels) as well as for processing or blending (the specifications in contracts in Europe do not allow for high CO_2 levels).

The case study presented is based on a real investment case from Norway. In particular, how an industrial cluster may utilize CO_2 rich gas is explored. The impact of different price reductions to account for the lower quality in the gas with high CO_2 content is also analysed. Different scenarios are analyzed, and the main findings from this case study are that there could be both environmental and economic benefits by using the CO_2 rich gas. The increase in CO_2 emissions is not as high as the additional input of CO_2. Furthermore, by adjusting the gas price for the disadvantages with CO_2 rich gas, the net present value for the cluster with CO_2 rich gas will be higher with the same production level. The technical study of the processes also shows that it is technically feasible to use this gas. These conclusions indicate that it can be an interesting investment opportunity to base an industrial cluster on CO_2 rich gas.

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