Use of Natural Gas with High CO₂ Content in an Integrated Industrial Park

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In this paper we analyse the economic and technical effects of using CO₂ rich natural gas in an industrial park. The basis for our work is a technical-economic description the processes in the different plants. A mathematical model is established that enable analysis and optimisation of design and operation of the industrial park. The model optimises maximizes the net present value of the available investment and operation opportunities. The candidate plants that we consider in our 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. We use Norway as a case study due to the political ambitions of increasing domestic consumption of natural gas to achieve a higher level of innovation and industrial development. Several scenarios are analysed, and the main findings from this case study are that there could be both environmental and economic benefits by using a CO₂ rich gas in an integrated industrial park.

KEY WORDS: carbon dioxide; natural gas; economy; direct reduced iron; steelmaking; methanol; carbon black; industrial park.

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). 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. 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. The main motivation for increasing the national consumption 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 also located in areas in Norway with limited employment options – this strengthens the political motivation for establishing such industrial parks. 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 situation where the distance to the markets are long, the field is 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 CO₂). 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, materials producing industrial parks. In Norway there can be a trade-off between processing the natural gas with high CO₂ content to meet the quality demand from the European customers and utilizing the gas directly in industrial process that can handle high CO₂ 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 park. In the case study we present in this paper the industrial park 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 park emit CO\textsubscript{2}, but the concentration of the CO\textsubscript{2} in the exhaust gas (and the amount of it) differs for the different plants. The CO\textsubscript{2} can be emitted to the environment, where it may be subjected to CO\textsubscript{2} taxes (equivalent to the price of CO\textsubscript{2} quotas), or a carbon capture plant designed for flexible operation can be installed to capture the CO\textsubscript{2} from some or all of the processes.

An integrated industrial park consists of a number of plants with different characteristics that produce different products and by-products. One of the benefits of industrial parks is that by-products, which are not technically or economically feasible to transport for long distances, can be exchanged. 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 in addition, the environmental costs can be reduced. However, the industrial park 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 park and can also require that one or more plants are operated off-design. The varying production levels in the plants in the industrial parks make it important for a carbon capture plant to be able to handle such variations, and operate as efficiently as possible. The industrial park that we consider in this paper is illustrated in Fig. 1.

The main contribution of this paper is an analysis of the economic and technical effects of using CO\textsubscript{2} rich natural gas in an industrial park. We illustrate this by considering a case study where we analyse how gas with a high CO\textsubscript{2} content will affect the optimum investment, operation and configuration of the industrial park. We use a system perspective in our analysis, meaning that we assume that one central planner makes all decisions in the industrial park. This gives a benchmark solution which is the highest achievable total net present value in the park. The coordination mechanisms used to align the decision makers in the industrial park will then decide how close to this benchmark solution the park will come. These considerations are however out of the scope for our analysis.

In Section 2 we present the methodology and main assumptions we have used in our analysis. A discussion of how the different plants that are included in our case study can handle natural gas with high CO\textsubscript{2} content is provided in Section 3. We then move on to presenting the case study and scenarios in Section 4. The results from the case study are given in Section 5, and we then conclude in Section 6.

2. Methodology and Assumptions

This analysis of high CO\textsubscript{2} gas in an industrial park 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 park 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 park. Based on these relationships we formulate a mixed integer linear programming model which is implemented in Xpress-MP (v. 2008a, Fico). The programming model offers flexibility regarding both the design of and the operation of the individual plants and the possible connections between the different plants. Thus optimization yields design and operation of the plants in a way that take care of the integrated park concept. For details regarding the optimization model, see Midthun et al.\textsuperscript{31} 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 optimization model is to optimise investment and operation of the park for a given case and scenario, which implies maximisation of net present value (NPV), defined as the present value of the cash flow (\(PV_{\text{cf}}\)) minus the present value of investments (\(PV_{\text{inv}}\)). Cash flow (\(CF_{\text{cf}}\)) include revenue from products and energy sold in the markets, costs of raw materials, operation costs, and CO\textsubscript{2} and NO\textsubscript{x} tax payments. Present value of invest-
ments comprises investments \( I_p \) in different plants or units \((p)\) that together make up the park. The objective function in our model is then:

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

where \( s \) is the tax rate, \( \gamma \) is the depreciation 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 park 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 park begins). Accordingly investments are not discounted as they accrue at time period 0 which is equivalent to present time. We further use the standard assumption that the particular company or companies always will be in a tax-paying position (either from the operation in the park or due to other businesses). This yield a simple adjustment for tax deductions due to depreciation of assets, see second term in the rightmost bracket of (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). We will use both these gas compositions in our analysis.

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. We consider two price adjustments in our 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:

\[
\text{Price}_{\text{high CO}_2} = \frac{GCV_{\text{high CO}_2}}{GCV_{\text{normal}}} \cdot \text{Price}_{\text{normal}} \tag{2}
\]

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 we subtract the price of the additional CO\(_2\), in accordance with the assumed carbon tax level.

\[
\text{Price}_{\text{high CO}_2} = \frac{GCV_{\text{high CO}_2}}{GCV_{\text{normal}}} \cdot \text{Price}_{\text{normal}} - (0.196 - 0.037) \tag{3}
\]

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

### 3. Modelling of the Individual Plants for High CO\(_2\) Content

In this section we outline the effect for the individual plants of using a natural gas feed with of CO\(_2\) levels substantially above export specification before we present the the analysis in Section 4 and 5 of the plants’ and park’s joint ability to make profitable use of such CO\(_2\) rich gas. 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\(^4\)\(^-\)\(^9\) for many years. Production of iron carbide\(^2\) and conversion of Natural Gas to Syn Gas\(^3\) 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

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**Table 1.** Properties of the two different gas compositions we have used.

<table>
<thead>
<tr>
<th>Gas property</th>
<th>Original</th>
<th>CO(_2) rich</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO(_2)</td>
<td>1.6%</td>
<td>8.6%</td>
</tr>
<tr>
<td>Higher hydrocarbons (C(_2)+)</td>
<td>9.7%</td>
<td>3.5%</td>
</tr>
<tr>
<td>Molecular weight, kg/kmol</td>
<td>18.8</td>
<td>19.2</td>
</tr>
<tr>
<td>Lower heating value, kJ/kg</td>
<td>47 038</td>
<td>39 836</td>
</tr>
</tbody>
</table>
gas loops around, and is heated by the heating gas in the burner. So in the burner, more gas is needed to supply the same amount of heat.

In the reforming loop, more gas is required to reduce the iron ore, since CO₂ 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.

Figure 2 shows the flow sheet of the DRI plant.

3.2. Steel Plant

In the steel plant, natural gas can 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), 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 m³/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. Annual cost savings may be approximately $7.1/tonne due to reduced tap-to-tap times. The payback time is estimated as 0.9 years.

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 (H₂) and carbon monoxide (CO). Then, in a synthesis section, methanol can be formed by \( 2\text{H}_2 + \text{CO} = \text{CH}_3\text{OH} \) or by \( \text{CO}_2 + 3\text{H}_2 = \text{CH}_3\text{OH} + \text{H}_2\text{O} \). Accordingly, increased CO₂ 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 our cases, this requires more H₂ and therefore a higher volume of natural gas.
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.\(^1\) 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 our industrial park case study are discussed in Section 3, and 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. Figure 1 illustrates the flow of the most important raw materials and finished products in the park. In addition, the figure also shows the possible interactions between the different plants. 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 park 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 park (see Fig. 1). 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 park, the DRI, steel, methanol and power plant emit \( CO_2 \). The offgas \( CO_2 \) 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 \( H_2 \) and \( CO_2 \)), 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 has higher \( CO_2 \) concentrations.

4.2. Main Assumptions and Scenarios

Optimum investment in the industrial park 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 we present the main assumptions related to this case, as well as the basis for the modelling of carbon capture investment and operations.

All the candidate plants in the park (except for the carbon capture plant) use natural gas as raw material. In the case study we use a time horizon of 20 years. In order to forecast values for the prices 20 years ahead in time we have used a prognosis made by the Norwegian Petroleum Directorate.\(^2\) The time profiles of the \( CO_2 \) taxes and the electricity price are based on a prognosis made by Statistics Norway.\(^3\) 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 we use in our analysis for natural gas, \( CO_2 \) taxes and electricity are shown in Fig. 3. For the material prices we have studied the historical relationship between the natural gas price and the materials price. These relationships have then been used to predict how the prices for the different materials will develop (the ratio to the natural gas price is assumed constant in our optimization horizon).

5. Results and Discussion

We present results for two different scenarios: scenario 1 and scenario 2. In scenario 1 only the power plant has to pay \( CO_2 \) taxes, while in scenario 2 all plants have to pay \( CO_2 \) taxes. 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, we also present the results from using the three different pricing alternatives presented in Section 2.3. 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 adjust-
ed. The resulting prices are shown in Table 2. For both sce-
narios we then find 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 CO₂ content
with price adjustments (NPV2 and NPV3). An overview of
the results is provided in Table 3, while the next subsections
will give a closer discussion of these results as well as illus-
trations of our main findings.

5.1. Investment Results
In scenario 1, where only the power plant is subject to a
CO₂ tax, it is optimal not to build a carbon capture plant. In
this situation, it is more cost efficient to pay taxes for the
CO₂ emitted from the power plant than to build and operate
a carbon capture plant. This result is independent of whether
original or CO₂ rich gas is used. In scenario 2, where all the
plants are subject to CO₂ taxing, the optimum cluster config-
uration includes a carbon capture plant. In this situation,
the carbon capture plant is used to capture CO₂ from all the
plants. In addition, the carbon black plant has become prof-
itable in scenario 2. The carbon black plant produces steam
which can be utilised in the methanol plant. This additional
supply of steam decrease the emissions of CO₂ 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 uti-
lize the synthesis gas from the carbon black plant.

5.2. Emission Results
When the industrial park is supplied with the natural gas
with high CO₂ content, the natural gas consumption increas-
ies with 16 to 18% compared with the cases with the original
gas composition. Correspondingly, the CO₂ input is about
five times higher in the CO₂ rich cases. This also results in
increased CO₂ produced in the park. However, the increase
of 5–8% is much smaller than the additional input (also in
absolute terms – see Table 3). For an illustration of the dif-
ference in natural gas consumption and CO₂ input, see Fig.

Table 3. 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 (BNOK). The abbreviation GCV stands for
gross calorific value.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Original gas</th>
<th>CO₂ rich gas</th>
<th>Difference</th>
<th>% increase from original gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas input, [tonnes/hour]</td>
<td>137.8</td>
<td>162.7</td>
<td>24.9</td>
<td>18%</td>
</tr>
<tr>
<td>CO₂ input (in the natural gas), [tonnes/hour]</td>
<td>5.1</td>
<td>31.9</td>
<td>26.8</td>
<td>527%</td>
</tr>
<tr>
<td>CO₂ produced in the park, [tonnes/hour]</td>
<td>229.5</td>
<td>247.8</td>
<td>18.3</td>
<td>8%</td>
</tr>
<tr>
<td>NPV 1 [BNOK]</td>
<td>27.2</td>
<td>19.7</td>
<td>–7.6</td>
<td>–28%</td>
</tr>
<tr>
<td>NPV 2 (GCV adjusted) [BNOK]</td>
<td>27.0</td>
<td>20.7</td>
<td>–6.3</td>
<td>–1%</td>
</tr>
<tr>
<td>NPV 3 (GCV and CO₂ adjusted) [BNOK]</td>
<td>28.8</td>
<td>22.5</td>
<td>6.3</td>
<td>6%</td>
</tr>
</tbody>
</table>

Fig. 3. The prices for natural gas, electricity and CO₂ quotas used
in the analysis. The left axis shows the price of natural gas and
CO₂ taxes in Norwegian kroner (NOK) per ton, whilst the right axis shows the price of electricity in Norwegian kroner per kWh.

Table 3. 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 (BNOK). The abbreviation GCV stands for
gross calorific value.
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, as explained in Section 3.

5.3. Economic Effects

In this subsection we compare how the three different gas pricing alternatives for the CO₂ rich gas, as described in Section 2.1, influence the economic results from our analysis. For an overview of these results, see Fig. 6. When the gas price for the two cases with different gas composition is equal, the net present value (NPV) for the industrial park when using the CO₂ rich gas decreases with approximately 30%. The configuration of the park, however, remains equal, and the park is profitable both with the original gas and the CO₂ rich gas.

We then adjust the natural gas price in accordance with the ratio between the heating values. For scenario 1 the resulting net present value when using the CO₂ rich gas significantly increases. 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 CO₂ concentration.

We then also adjust the natural gas price for the CO₂ content directly, by compensating for the CO₂ tax (i.e. carbon quota price). In this alternative the net present value (NPV2) is higher in the CO₂ rich gas cases for both scenarios. The difference between the net present value from the high CO₂ gas analysis and the original gas analysis is, respectively, 6 and 12%.

The changes in net present value between cases using original gas and CO₂ 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 in the rich CO₂ gas cases, because of the increased total amount of CO₂ that is captured. The amine usage and costs are correspondingly also higher. When a carbon capture facility is not built, then the total CO₂ taxes are approximately 7% higher when using the CO₂ rich gas. On the other hand, using the CO₂ rich gas results in higher steam production and also higher production of synthesis gas, which are utilised 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 CO₂ rich gas. The additional CO₂ emissions for the CO₂ 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 CO₂ emitted from the park is found be almost invariant with respect to the level of CO₂ in the gas supplied. By adjusting the gas price for
the disadvantages with CO₂ rich gas (lower heating value and “compensation” for increased carbon taxes), the net present value for the park will be higher for the same end products produced. This could make it sustainable both environmentally and economically to use CO₂ rich gas in material producing industries.

6. Conclusions

In this study we have presented a decision support model for an integrated industrial park. The park 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 park as well as optimal operation of the installed equipment over a given time horizon.

Given the increased focus on CO₂ emissions, such as discussions regarding mandatory carbon capture and emission taxes, we have explored the possibility of utilizing CO₂ rich natural gas in such industrial parks. The motivation for such studies is further strengthened by exploration of smaller gas fields on the Norwegian Continental Shelf which may contain high levels of CO₂. The CO₂ rich gas poses challenges both for transportation (due to restrictions on content in gas pipes not designed for high CO₂ levels) as well as for processing or blending (the specifications in contracts in Europe do not allow for high CO₂ levels).

The case study that we present is based on a real investment case from Norway. In particular, we have explored how an industrial park may utilize CO₂ rich gas. We have also analysed the impact of different price reductions to account for the lower quality in the gas with high CO₂ content. Different scenarios are analysed, and the main findings from this case study are that there could be both environmental and economic benefits by using the CO₂ rich gas. The increase in CO₂ emissions is not as high as the additional input of CO₂. Furthermore, by adjusting the gas price for the disadvantages with CO₂ rich gas, the net present value for the park with CO₂ 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 park on CO₂ rich gas.

REFERENCES