Technical assessment for Onsite co-generation systems in Industry, Commercial and Transport sectors on Natural Gas

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# Acronyms and Symbols

* CHP – Combined Heat and power
* CO2 – Carbon dioxide
* EPA – Environmental Protection Agency
* ETP – Energy Technology Perspectives
* EU – European Union
* GHG – Greenhouse gases
* IEA – International Energy Agency
* Ppm - parts per million
* TAM – Total Addressable Market
* USA – United States of America

# Executive Summary

Co-generation, or Combined Heat and Power (CHP), refers to systems which produce both electricity and thermal energy from a single fuel source at the location of off-take. Being used as distributed energy systems, they help to reduce energy consumption, and corresponding emissions, in two ways: by capturing and utilizing excess heat produced during power generation, and by replacing the use of electricity from the grid with onsite generation avoiding transmission and distribution losses inherent in centralized power systems. CHP is a well-established energy production method which may be modified to accommodate a variety of end users within the industrial, commercial, transport, and residential sectors for the production of power, process heating, and district heating. CHP can utilize a variety of fuels, both fossil and renewable.

In 2014, co-generation systems accounted for about 15% of global power generation. Regarding heat supply, co-generation units represented 6.8%. The majority of currently installed co-generation units are fueled by fossil fuels. Coal represents around 54% of total CHP electricity generation, natural gas provides 39% and oil CHP generates 2.5% of electricity from co-generation systems. However, this also depends on the application as an increasing number of co-generation systems utilize renewable energy sources. Globally, 55% of all CHP systems generating electricity are auto producers while 45% are main activity producers

Many countries have enacted policy to promote the adoption of CHP and it is viewed as playing an important part in the transition to a clean and renewable energy future. Further, the flexibility and financial benefits of CHP make it an attractive option for end users. Herein, we focus on auto producer CHP systems running on natural gas which currently represent around 3.2% of total electricity generation.The analysis is not looking at district heating and discounts the potential for increase in diversified renewables as part of the CHP generation mix. The topics of district heating and the use of waste and biomass in CHP plants have been addressed in other Project Drawdown solutions.

In this report, the increased adoption of CHP has been analyzed as well as its climate and financial impacts. The analysis takes the view that CHP is a replacement solution from the use of electricity from the grid under the current electricity generation systems and heat boilers that produce heat. An optimistically plausible scenario in which the share of our solution increases around 80% from the current level, is compared to a business as usual scenario in which the share remains fixed at the current level. The analysis is conducted within the framework of Project Drawdown’s Reduction and Replacement Solutions core model and is supported on two separated models created for the effect: one regarding the electricity generation and the other the heat production.

Future adoption is derived from an analysis of several scenarios of EU AMPERE (2014); Greenpeace (2014) and IEA ETP (2016). The results indicate that increasing CHP auto producers on natural gas adoption in all sectors (commercial, industrial and transport) from 3.2% in 2014 to 6.24% of world electricity generation while the heat supply met by CHP increases from 1.7% to 2.9% in the same period by 2050 is estimated to cost US$284 billion and US$8.6 billion in cumulative and marginal first costs respectively, according to the modeling results. This assumes an average installation costs at US$1845 a kilowatt (based on the meta-analysis of several data points) and O&M costs of $0.0118 cents/kWh. The net operating cost savings from the combined heat and electricity generation for 2020-2050 would be near US$417 due significantly to lower fuel use and costs over a business-as-usual scenario. When looked at over the full lifetime of CHP adoption from 2020-2050, lifetime savings in net present value (NPV) will be US$4.79. The combined climate impact of increased adoption of CHP auto-producers running on natural gas by 2050, indicates that this solution could reduce emissions by 4.07 billion tonnes (Gt) by 2050. This will drawdown global CO2 in the atmosphere by 0.39 ppm.

The results of this study confirm that significant economic, energy, climate change mitigation would result from the increased adoption of CHP technologies across all sectors globally. Government, regulators and all those who are seeking to promote sustainable energy use towards climate mitigation will also need to focus of how to make CHP adoption one of the key strategies.

# Literature Review

## State of Co-generation

Co-generation, also known as Combined Heat and Power (CHP), is the combined production of useful thermal energy and electricity from a single fuel source. In general, CHP systems function by capturing the excess heat generated during electricity production and using this thermal energy to meet demand at or close to the location where the system is located. Therefore, CHP systems are a distributed energy resource. Co-generation helps to reduce fuel use, and consequently reduce emissions, in two ways. First through the recovery of heat; since a large part of what would otherwise be lost during conversion in conventional power generation or heat production is turned into useful energy. Secondly, because co-generation systems are located at the site of off take, transmission and distribution losses are avoided. As seen in Figure 1, due to better efficiency, co-generation plants can produce the same units of heat and power forms of energy using less fuel as compared to separate heat and power production systems.

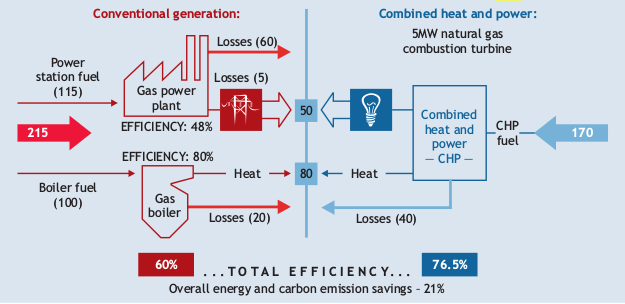


Figure 1: Comparison of CHP plant and separate heat and power system in terms of energy and carbon emissions saving using the example of a 5MW natural gas combustion turbine CHP system (IEA, 2008).

Co-generation systems generally consist of a prime mover, an electricity generator, a heat recovery system, and a control system. Primarily, there are two types of CHP systems – topping and bottoming cycle. In a topping cycle system, fuel is used first in a prime mover such as a gas turbine or reciprocating engine to generate electricity. The excess heat from the production of electricity feeds a heat recovery system to provide process heat, hot water, or space heating and/or cooling. Typically, topping-cycle CHP systems are sized to optimally meet baseload thermal heat. In a bottoming cycle CHP system, (also known as waste heat to power) thermal energy is first produced by an input fuel to a furnace or other high temperature industrial process. Excess heat is then recovered and then used for electricity production typically in a heat boiler/steam turbine system (DOE, 2012).

Co-generation systems are commonly classified according to their application, prime mover, and fuel. The best applications for cogeneration are in facilities with consistent electric and thermal loads including: hospitals, schools, recreational facilities, industrial facilities, hotels, and nursing homes. CHP is primarily found in areas with high concentrations of industrial and commercial activity, high electric rates and policies favorable to CHP.

CHP systems can also be distinguished due to two distinct situations, depending on whether the heat use is at high temperatures (fuel burned primarily for heat) or at low temperatures (fuel burned primarily for electric power). A) Energy intensive industries often have both a large electricity demand and a requirement for high temperature process heat. In these industries, heat is the primary product, and electricity secondary. This can be applied to an industrial process that releases relatively low quantities of high-temperature waste heat, for example a steel mill, or a food processing plant. The CHP component typically generates electricity for the plant itself or to feed back into the grid. When the heat is not needed, no electric power would be generated.

B) Residential or commercial low-temperature heating where electric power is primary. This is usually an electric generator (for example a large central steam turbine, or smaller gas turbine), which releases high quantities of relatively low-temperature waste heat. The CHP component here then uses that waste heat for residential and commercial heating (or possibly industrial processes that need only those lower temperatures). The heat is available only when the generator is running.

These varied applications necessarily imply a range of system sizes from large to micro scale. Prime movers used in co-generation systems, such as gas turbines, steam turbines, and reciprocating engines, are mostly mature and reliable technologies and are typically used in larger scale applications. Newer technologies, such as micro turbines and fuel cells, are showing promise for use in small scale applications (EPA, 2015).

## Adoption Path

Data for 2012 from Greenpeace (2015) states that globally, district heating plants provided 5.6% of total heat supply, co-generation units 6.8% and direct heating from boilers and heat pumps represented 87.6%. On electricity generation, CHP units accounted for 15% of global generation (Greenpeace, 2015).

The majority of currently installed co-generation units are fueled by fossil fuels. Coal represents around 54% of total CHP electricity generation, natural gas provides 39% and oil CHP generate 2.5% of electricity from co-generation systems (Greenpeace, 2015). However, this also depends on the application as an increasing number of co-generation systems utilize biomass, waste, and geothermal resources (IEA 2011).

Globally, 55% of all CHP systems generating electricity are auto producers while 45% are main activity producers. At a regional scale, there are significant differences, with Latin America and China having 100% of CHP as auto producers directly linked to industries, transports and other sectors and OECD Europe and Eastern Europe with 71% and 93% of CHP of main activity producers, respectively (Greenpeace, 2015).

Many of the co-generation systems which are currently on line are found in the industrial sector. In the US, for example, 87% of CHP systems are used in energy intensive industries such as chemical, paper, food processing, and metal manufacturing (DOE, 2012). On the other hand, in countries such as Denmark and Finland, co-generation makes up a significant part of electricity production largely due to their use in district heating systems. Nonetheless, global electricity generation from CHP has stood at around 15% in the last years (Greenpeace, 2015). By major world regions and according to Greenpeace (2015) CHP systems provided in OECD North America 7% of total electricity and 4% of total heat, in OECD Europe 23% of total electricity and 8% of heat, in China 27% of electricity and 8% of heat. Regions has Middle East and Africa and India did not have any CHP systems in place in 2012 (Figure 2).

Figure 2 – Electricity and Heat generated form CHP systems in different world regions

Given that co-generation is a mature and proven technology, it is used in a variety of applications and can be fed with both fossil fuels and renewable energy sources (biomass, waste, geothermal, solar).

Though, there are certain policy and financial barriers which impede its global adoption. These include market conditions which fail to incentivize energy efficiency, a poor dissemination of knowledge about the benefits of co-generation, and the uncertainty in long-term energy infrastructure planning. In some cases, local building and zoning codes inadvertently prohibit the installation of co-generation (Kalam *et al*., 2012; DOE, 2012; EPA 2014). CHP systems are often sized to meet thermal load. This may lead to situations where users find it necessary to sell excess power back to the grid. On the other hand, given a particular capacity factor, CHP systems may not be able to meet the user’s electricity demand at all times (Athawale and Felder, 2014). Becoming a player in the interconnected electricity grid and addressing the issue of economic dispatch may be beyond the core business model of the facility where the CHP plant is operating and thus present a business risk for the owner (Yazdani A *et al*., 2013, Vasebi A et al., 2007).

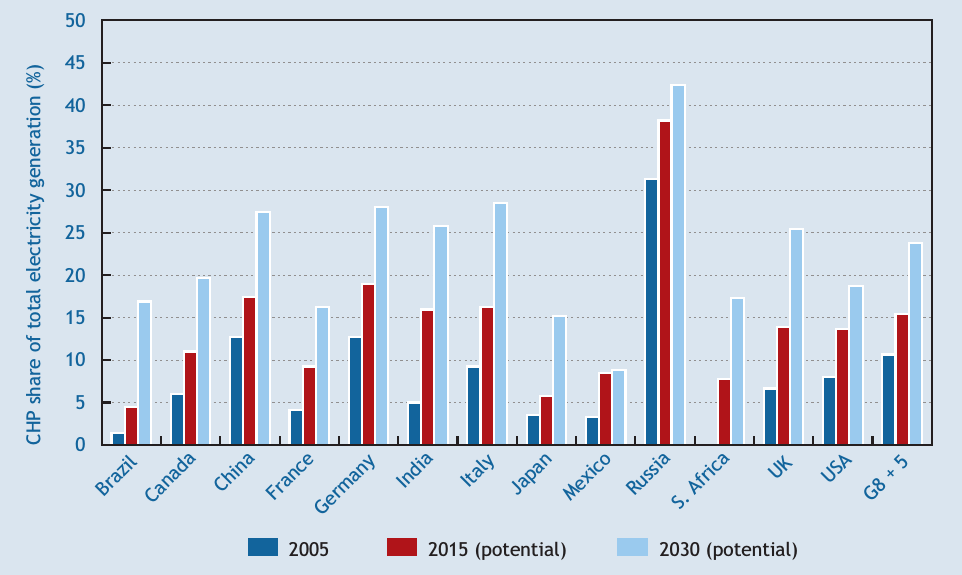


Figure 3: CHP potential in various countries under an accelerated scenario (IEA 2008)

Despite these barriers, the potential for CHP implementation in many countries is significant. The International Energy Agency analyzed this potential in its 2008 report. The results, illustrated in Figure 3, show a small increase in capacity in the short term, with a larger increase occurring after 2015. To be sure this analysis assumed an accelerated deployment of CHP in these countries which would mimic the rate of growth seen in countries such as Denmark and Finland. This accelerated growth has not occurred and so in the USA, for example, CHP continues to make up around 8% of the country’s total electric generating capacity (EPA, 2015a). Similarly, in Japan, as of 2012 CHP share of total electricity generation remains below 4% (Pales AF, 2013).

Notwithstanding this evidence of stagnant uptake, certain best practices do highlight effective drivers for co-generation deployment. In countries with a high CHP share in total generation, such as Denmark and Finland, the need to address issues of energy security and efficiency has played a decisive role. Each country has taken a unique path to adoption however; with the former resulting in large part from specific government policies and the latter being more market driven. Finland’s large paper and forestry industries have natural motivation to utilize biomass based CHP systems due to the onsite availability of this renewable energy resource. Moreover, the cold climate in the country has provided a basis for healthy return on heat supply infrastructure investment. As of 2013, 69% of the country’s district heating is provided by CHP systems (Pales AF 2013a). Denmark’s approach to energy supply has been more policy driven. Although the use of CHP in the country dates back to 1903, it was the oil crisis of the 1970s which really spurred the use of this technology. Since that time, subsequent policies have compelled local authorities to identify opportunities for energy efficient heat production, helped to move power generation from centralized plants to a decentralized network, and incentivized the use of CHP generally, and renewable based systems particularly, through tax policy. Additionally, Denmark has actively participated in UN climate change negotiations and made advances to reduce their greenhouse gas (GHG) emissions; around 80% of district heating and over 60% of electricity demand is met by CHP (Kerr 2008).

The development of CHP in Europe and the USA is well documented. On the other hand, several countries which could potentially benefit from this solution lack accurate data of current trends. This hinders the successful deployment of the solution. Nevertheless, exemplary cases in India, South Africa, and Brazil do highlight the benefits which CHP could offer in those countries and others in the developing world. The Indian government has made efforts to reduce its GHG emissions and towards this end has, since 2013, approved 50 CHP projects under the Clean Development Mechanism of the Kyoto Protocol. While these projects make up less than 0.2% of the country’s total electricity generation they have mitigated 2.5 megatonnes of CO2 per year (Pales AF West K 2014). In South Africa, the government has sought to procure 1800 MW of cogeneration capacity through its Medium-Term Mitigation Project (Department of Energy, 2015). Among the projects already registered is a 200 MWe natural gas powered CHP plant at the Sasol facilities in Johannesburg. This project has allowed the large synthetic fuel producer to lower its dependence on the country’s electrical grid, thus reducing the risk of power shortages (SANEDI 2014). The development of biomass and bagasse based cogeneration systems in Brazil has been steady and relatively well documented. Yet, there is a large potential for cogeneration in connection with the natural gas used in industry and electricity production (Matelli and Ferreira, 2012). This is especially relevant as droughts, which become more frequent, threatens the supply of electricity from hydroelectric dams (Cunningham, 2015). Cogeneration is also used in small island nations. For example, Mauritius and Barbados both utilize bagasse fueled co-generation systems in their respective sugar industries (Deepchand K& Nath, 2011, Wellington & Moore, 2001).

## Advantages and disadvantages of co-generation systems

Co-generation is essentially a form of recycling in that energy that would otherwise be wasted as heat is recaptured and put to use. The technical components of these systems may vary, so that co-generation systems may be fed by fossil fuels or renewable energy e.g. geothermal, solar and that these fuels may be utilized by a variety of prime movers to produce electricity and heat. In this respect, alternative solutions which might address the issue of low efficiency in generation units would, in order not to be lumped in with co-generation, have to deal strictly with increasing the efficiency of engines and turbines and not with the recapture of lost heat. In theory, this means that it would be very difficult for separate heat and power systems to reach the efficiency of combined units. This is exemplified in practice by comparing the most efficient separate heat and power systems to the least efficient CHP systems. For example, combined cycle gas turbine power plants, which utilize two thermodynamic cycles and thus improve the overall efficiency of systems, can reach efficiencies of 60% (Robb, 2010). CHP system efficiencies generally range from 65% to 80%[[1]](#footnote-1) (EPA, 2015). Applying these numbers to those of Figure 1 we see that the most efficient use separate heat and power systems and the least efficient CHP systems have about the same overall efficiency of 67%. Even so, considering that combined cycle technology may also be applied in CHP systems, it seems that the latter still would provide more fuel savings and other economic benefits than the former.

To look at this another way, we may compare separate heat and power and co-generation systems by the heat to power ratio, a measure of the proportion of energy a prime mover will release as power as compared to that released as heat. In separate generation systems, this becomes critical as the efficiencies of thermal units usually are far greater than that of power units. As can be seen in Figure 4, as the power to heat ratio becomes larger, i.e. more power is being produced than heat, so does the difference in efficiency between CHP and separate generation systems.

Compared to natural gas boilers, CHP has several economic and operational advantages, such as reduced operating costs, the value of the electricity produced by the CHP system is greater than the additional fuel and O&M costs associated with the CHP system.

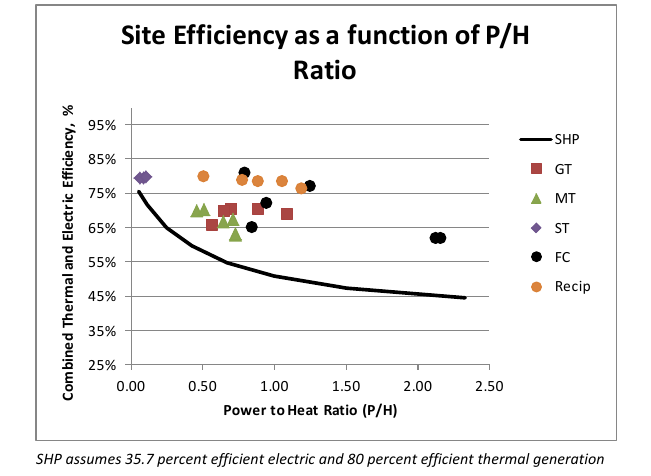


Figure 4: Comparison of SHP (Separate Heat and Power) and CHP systems based on power to heat ratio (EPA, 2015)

Strictly from a financial view then, with all other things being equal, the adoption of CHP systems seems to make sense for industrial, commercial, and residential users. The fact that they produce more energy for the same amount of fuel proves this. Also, through the highly efficient production of steam and electricity onsite using e.g. natural gas as a fuel, CHP can provide a hedge against increasing electricity costs by reducing electricity purchases from the grid (McNeil, 2013).

Apart from financial benefits to users, this characteristic of co-generation systems also implies that their increasing adoption will reduce GHG emissions regardless of the fuel being used. Moreover, CHP will play a substantial role in the ushering in of smart, distributed and renewable based energy networks. Because these systems are necessarily placed close to the site of off take, they not only reduce the need for transmission lines and provide enhanced power supply reliability, mitigating or eliminating the potential costs associated with electricity supply disruption. CHP systems can be designed to operate independently of the grid and provide the host facility with the ability to maintain operations —partially or completely, depending on design —during grid outages (McNeil, 2013).

It also allows the user to have a more involved role in the production of energy. Involving the user is an essential component of smart energy systems (Hvelplund et al., 2014). CHP systems are easily adaptable to user preference and thus allows for the use of a variety of renewable energy sources as fuel including solar, wind, biomass, and biogas. Additionally, CHP systems use negligible amounts of water when compared to separate heat and power systems, thus decreasing demand pressure on another vital natural resource (EPA, 2015).

The main environmental advantages of CHP running on natural gas or RES is a reduction of GHG emissions and other air pollutants compared to coal or oil boilers. Since they consume less fuel to produce each unit of output it reduces emissions.

CHP systems also have a few disadvantages since, CHP is more a means of making other energy sources more efficient rather than an intrinsic energy source. Also, some critics fear that its use will prevent full development of 'true' renewable energy sources.

It is also only suitable for use where both heat and electricity are needed, and at consistently high and sustained levels (Kinsley, 2014). Thus, the applications require the right combination of thermal and electric load (Rutgers, 2013). Furthermore [heat is lower-quality energy than electricity](http://arthur.shumwaysmith.com/life/content/the_problem_with_heating_efficiency_chp_critique_part_2), and only at high temperatures does it become close to comparable. Efficiency claims for CHP systems that use high-temperature heat are not so far off, but CHP systems that make use of low-temperature waste heat have much lower thermodynamic efficiencies than usually claimed.

Development of the systems can be expensive, and the technology cannot truly be deemed as being sustainable in the long term when it is used to extract efficiencies from fossil fuels (Kinsley, 2014).

# Methodology

An analysis of the financial and environmental impacts of cogeneration adoption in the industrial sector has been performed. The analysis was conducted using Project Drawdown’s Reduction and Replacement Solutions (RSS) core model.

The analysis will focus on CHP adoption in the industrial sector using natural gas replacing current use of electricity from the grid and diesel heat boilers. District heating has been covered elsewhere in the Project Drawdown. Therefore, the analysis takes as its point of departure data on the current share of CHP on total electricity and heat generation, evaluating the share between auto producers (related to industrial activities) and main activity producers and the current fuel mix used globally in CHPs.

CHP running on natural gas is viewed herein as a transition solution to fully decarbonized power system, It is considered and assessed in our models as a solution threefold: 1) due to the reduced used of electricity from the grid cutting transmission losses, improving the efficiency of the system; 2) due to the fuel shifting to natural gas from oil boilers that produce heat reducing GHG emissions and other air pollutants, and 3) due to the greater efficiency of CHP than conventional separate boilers and generators.

Co-generation is unique in that it addresses both the electricity and heat markets. Therefore, the model utilizes separate, albeit linked, addressable markets for each of these energy commodities.

## Data Sources

Information on CHP technical and economic characteristics was taken from a variety of source literature, including but not limited to reports from governmental and international bodies and peer reviewed publications. The information gathered includes adoption pathways of CHP technologies, capital and operation and maintenance costs, efficiencies and technology lifetimes.

For all our variable inputs, we conduct a meta-analysis of existing literature to create low, high, and mean estimate. This allows us to calculate robust and reliable inputs for our financial and climate analyses that represent both optimistic and conservative estimates for the future costs and benefits of this solution.

### Total Addressable Market

As stated, the analysis presented here concentrates on the potential for onsite CHP systems in the industrial sector running on natural gas. To determine the total addressable market (TAM) for this solution it was necessary to collect global heat and electricity generation projections. Adoption of CHP systems coupled with industries will lead to a corresponding reduction in GHG emissions due to fuel shifting and electricity grid replacement. Moreover, it is hoped that CHP use will lower costs and thus make this particular climate change mitigation solution financially attractive to investors.

Two TAMS were created to assess the role of increased adoption of CHP under a Heat TAM and a Electricity TAM. Under the Heat TAM we assess the role of CHP for generating heat replacing conventional diesel boilers and using the Electricity TAM we evaluate the impact of the adoption of onsite CHP units to generate electricity replacing electricity consumed from the grid.

Therefore, because our BAU adoption scenario is framed in terms of percent of total electricity generation (and percentage of heat), we needed to project total electricity and heat demand during the period of analysis from 2015-2045. The electricity TAM for CHP is the same TAM used for the other electricity generation technologies. The functional unit for this solution is TWh of electricity generated and the implementation unit is TW.

**Electricity TAM**

As discussed in the Drawdown report “Electricity Generation Market Methodology” three TAM prognostication scenarios driven by distinct climate mitigation expectations (*Ambitious, Conservative* and *Baseline*) and all the underlying assumptions were calculated, averaged from comparable scenarios of each of the sources.

The scenarios were grouped in the Drawdown model to be included under the following cases for analysis:

* *Baseline Cases:* represent scenarios where current policies remained fixed over time. Scenarios include and the IEA 6DS Scenario (2016), AMPERE IMAGE REF pol (2014), and AMPERE MESSAGE REF pol (2014).
* *Conservative Cases:* represent conservative emissions mitigation pathways. Scenarios include the Greenpeace (2015) Reference Scenario, AMPERE (2014) GEM E3 550, AMPERE (2014) IMAGE 550, AMPERE (2014) MESSAGE 550 and the IEA (2016) 4DS scenario.
* *Ambitious* *Cases:* represent more aggressive actions to achieve major emissions reductions needed to put the world on the path under 2°C average temperature increase, the internationally-agreed threshold for avoiding potentially irreversible climate change. Scenarios include the IEA (2016) 2DS scenario, AMPERE (2014) GEM E3 450, AMPERE (2014) IMAGE 450, AMPERE (2014) MESSAGE 450, Greenpeace (2015) Energy Revolution Scenario.
* *100% RES2050 Case:* The Greenpeace (2015) Advanced Energy Revolution Scenario was used as benchmark for the highest level of RES adoption since it envisages 100% RES adoption for electricity generation by 2050.

The results from the different sources are given for every 5 or 10 years. To determine annual electricity generation values, data interpolation methods were used to create best fit trends (*i.e.* 3rd polynomial trends applied between reported data). The results were also harmonized to the UN 2015 medium population scenario (UNDESA, 2015).

**Heat TAM**

Currently industrial heat at a global level is supplied by district heating plants, direct heating from boilers, heat pumps, solar thermal panels, and cogeneration units. For the Heat TAM, data from the Greenpeace Energy Revolution (2015) scenarios for 2012 to 2050 were used and allocated under the three Drawdown scenarios. The other sources (i.e. AMPERE and IEA ETP) used for the electricity TAM did not provide total heat supply.

Following the same approach as for the electricity TAMS; Greenpeace Reference Scenario was allocated under *Conservative;* Energy [R]evolution to *Ambitious* and Advanced [Energy] revolution to a higher benchmark, driven by the underlying assumptions from Greenpeace on very high adoption od RES.

The results from the different sources are given for every 5 or 10 years. To determine annual production values, data interpolation methods were used to create best fit trends (*i.e.* 3rd polynomial trends applied between reported data). The results were also harmonized to the UN 2015 medium population scenario (UNDESA, 2015).

Since we wanted Therefore, for our analysis, we considered to use the *Conservative* TAMs depicted in both RSS models comparing the solution with continuation of the current trend and not with pathways already considering a strong increase of the adoption of alternative electricity and heat generation solutions.

### Adoption Scenarios

As is the case with all Project Drawdown solutions, a Business as Usual (BAU) and an Optimistically Plausible (OPT) Scenario are formulated. These two scenarios are then compared to determine economic and climate implications of adopting the solution, in this case co-generation. These scenarios are both constructed using TW as an adoption unit of measure and TWh as an operational unit of measure. Assuming a certain share of future solution adoption, for each of the scenarios, both the power and heat shares in their respective addressable markets are determined.

Estimates of electricity generation and heat production from onsite cogeneration units are estimated from the results of several sources. While using different methodologies, several entities disclose their projections on the role that different technologies might have in the future under certain conditions. Typically, perspectives on technology learning curves and technological improvements (*e.g.* capacity factor) are used within energy system models or other similar analyses to characterize technologies and assess their future adoption.

As previously mentioned, for our global and regional adoption scenarios, we selected three sources, the International Energy Agency Energy Technologies Perspectives (2016); Greenpeace Energy Revolution (2015) and EU project AMPERE (2014). From these sources, we included 12 different scenarios to show a wide range of results projecting the role of CHP technologies, specifically onsite cogeneration systems in industry, in the future global electricity and heat generation mix. These assessments relate specifically to different climate mitigation pathways or RES adoption.

Not all the sources explicitly depict future adoption of CHP units by sector and fuel used. Thus, in order to get distinct adoption pathway scenarios for the solution, a few assumptions were made, as follows:

1. Regarding electricity generation, only Greenpeace provides separate values of the generation from CHP plants, which represented in 2012, 15% of total generation. This share was applied to the total electricity generation projections from the REFpol, 450 and 550 scenarios of AMPERE models MESSAGE and IMAGE and the three scenarios from IEA ETP (20016) (i.e. 6Ds, 4DS, 2DS).
2. Total Heat demand generated from CHPs is available for all the scenarios of the data sources used. According to the data depicted in Greenpeace it represented in 2012 around 7% of total heat supply.
3. The split by type of CHP unit and the type of fuel consumed are only disclosed in Greenpeace Scenarios for electricity generation. The share provided by Greenpeace in its base year (2012) for auto producers is 54,7% and the remaining 45,3% is for main activity producers.
4. The share of CHP units by fuel type is also only presented by Greenpeace (2015). Natural gas systems represented 38,8% of total CHP electricity generation.
5. The solution considers onsite cogeneration (i.e. auto producers) units in industry, commercial and transport sectors running on natural gas. The current adoption was obtained from the average number interpolated for 2014 from all the sources, and applying the auto producers share and natural gas share to total heat and electricity generation scenarios.
6. For the adoption scenarios presented in the “adoption data” sheet of the two RRS models, these two shares were kept constant representing a very conservative perspective (Figure 5).
7. Three more aggressive alternative pathways for the solution were calculated using the average adoption of the *Baseline, Conservative, Ambitious* scenarios. We considered a linear growth of the current share of auto producers from 54,7% to a maximum of 61% in 2050, as simulated under the Energy [R]evolution scenario from Greenpeace. This was combined with the increased adoption of natural gas, reaching 70% in 2050. These calculations are depicted in the “Custom Adoption” sheet. The average of these calculations are the ones used in the model to calculate the climate and financial impacts of the solution.
8. We have harmonized all the results of electricity and heat generation using electricity per capita for the medium scenario of 2015 revision of the United Nations population projections (UNDESA, 2015).

Comparing the scenarios of all the sources we can see a clear difference from the results on electricity generation of CHP units from Greenpeace and the others sources. The Energy [R]evolution scenarios (Greenpeace, 2015) foresee a shift in the heat sector towards an increasing direct use of electricity, thanks to the enormous and diverse potential for renewable power and the limited availability of renewable fuels for high temperature process heat in industry. In addition, a fast expansion of the use of district heating and geothermal heat pumps is assumed, leading to an increase in electricity demand, which partly offsets the efficiency savings in these sectors. In the Advanced Energy [R]evolution scenario hydrogen replaces 30-40% of the remaining gas consumption in 2040 and 100% in 2050 – not only for industry, but also for power production in cogeneration and gas power stations, providing back up capacities for variable power production as from wind and PV scenarios (Greenpeace, 2015).

Figure 6 – Electricity generation scenarios from CHP units keeping constant the current shares for auto producers and natural gas from 2012 to 2060 for each scenario

### Business-as-Usual Scenario

**Electricity**

In the BAU scenario under the RSS CHP electricity model, the share of electricity generation from onsite CHP units running on natural gas is assumed to remain at around 3,2% throughout the years up to 2045. Within industry, CHP generated about 718 TWh of electricity in 2014.

**Heat**

In the BAU scenario under the RSS CHP heat model, the share of heat production from onsite CHP units running on natural gas is assumed to remain at around 1,7% throughout the years up to 2045. Within industry, CHP units produced near 736 TWh of heat in 2014.

Of course, maintaining constant share of electricity and heat generation from CHP within the industrial sector necessarily implies an increase in CHP systems as energy demand increases. Therefore, in 2045 CHP covers 1595 TWh of onsite industrial electricity demand and just over 1000TWh of heat demand.

### Optimistically Plausible

The intention of the optimistically plausible scenario is to support high GHG mitigation potential and RES penetration. As presented in the previous section, besides considering a growth of CHP adoption; three customized adoption paths were built contemplating an increase of CHP auto producer systems running on natural gas in both models. Our OPT scenario is driven by an average of all these three customized scenarios.

In 2045, this scenario projects the solution to represent 5,8% of the electricity generation market and 2,9% of the heat supply market.

## Climate and Financial Impacts

In order to derive the financial and environmental implications of applying the BAU and OPT scenarios to the total addressable market, several factors related to the functioning of CHP systems have been taken into account.

### Financial Inputs

The analyses of the economics of CHP technologies depends on the cost and performance of the various CHP technologies. We model both the capital costs and the operating and maintenance costs associated with the OPT scenario compared to those of the BAU scenario where electricity generation market remains dominated by coal, gas and oil sources and the OPT scenario for heat where the conventional technology are oil/diesel boilers. Since the cost and performance of CHP technologies vary, this study used a meta-analysis of global, regional and national cost and performance data for CHP to obtain mean input values for analysis in the model.

In order to identify the potential impacts of onsite CHP fueled by natural gas adoption, several assumptions were established for conventional electricity generation technologies (mix of oil, coal and gas fired power plants) in the DRAWDOWN RRS “CHP Electricity “model, as follows:

* Average lifetime of conventional electricity generating sources is 33 years. We average lifetime values across several different sources depicted in the model (see Variable Meta-analysis sheet).
* Average capacity factor for conventional electricity generating sources is 54 percent. We average capacity factor data for conventional sources across a number of different regions and installation sizes.
* A weighted average of the costs, efficiencies, capacity factors, and emissions of coal, natural gas and oil generating technologies are used for the conventional electricity grid. These weights are taken from total 2014 global electricity generation. The historical generation was collected from The World Bank Data in The Shift Project Data Portal.
* Fixed and variable operating costs, as well as average fuel costs are assumed constant through the modeling period.
* Fuel costs were collected from IEA (2016b) using an average of 2007-2016 data. An average value of 0,0733$2014/kWh for the grid mix (Conventional) and 0,0425$2014/kWh for natural gas for industry (Solution) are being considered.
* There is no price on carbon. As a result of the uncertainty related to carbon pricing and the policies required to ensure its implementation, its potential impact is not evaluated in this analysis.

Assumptions were also made in the “CHP Heat model” In order to identify the potential impacts of onsite CHP units fueled by natural gas compared to conventional diesel boilers, as follows:

* Average lifetime of conventional oil boilers for heat production is 18 years. We average lifetime values across several different sources depicted in the model (see Variable Meta-analysis sheet).
* Average capacity factor for conventional boilers is 91 percent. We average capacity factor data for conventional sources across a number of different regions and installation sizes.
* An average of the first costs of 77$/kW is adopted for conventional boilers, from figures of the sources used (e.g. NERA and AEA (2009); Energinet (2012); EPA (2013)).
* An average thermal efficiency of boilers of 77% is considered (average from IEA ETSAP (2010) and EPA (2012) figures).
* Fixed and variable operating costs, as well as average fuel costs are assumed constant through the modeling period.
* Fuel costs were collected from IEA (2016b) using an average of 2007-2016 data. An average value of 0,0975$2014/kWh for oil (Conventional) and 0,0425$2014/kWh for natural gas for industry (Solution) are being considered.

For the solution, 20 capital cost estimates from several data sources (*e.g.* IEA, 2008; IEA ETSAP, 2010; DOE, 2012 and Rutgerss, 1015) were used for installations in EU countries as Greece, USA and India. A wide range of costs for installing CHP gas units are presented in the RSS model, from US$ 941 (CRES, ND)) to US$2014 3277 per kilowatt (Rutgerss, 2015) which is much higher than average prices for conventional power plants based on fossil fuels. This numbers were analyzed to determine the average capital cost. Available data points were mainly from different installations in the USA.

Cost estimates for variable operation and maintenance (OM) of CHP plants were collected from a variety of sources (IPCC (2012); NRDC (2013); EPA (2015), and others). Variable operational cost range from 0.004 US$/kWh to 0.06 US$/kWh.

Fixed operation and maintenance costs (FOM) for both CHP units and conventional generation technologies can include expenses such as day-to-day preventative and corrective maintenance, labor costs, asset and site management, and maintaining health and safety, among others (Lo, 2014) and were retrieved for the solution from IA ETSAP (2010) and Rutgers (2015) varying from 13 $/kW to 330 $kW.

These estimates were used to calculate average variable and fixed operating costs of the solution, which, combined with capital costs for installation, represent the total financial costs of adopting this solution in the OPT scenario.

Technical parameters used in the model for the emissions and financial calculations as average annual use, lifetime capacity and plants efficiency were retrieved among others from IEA ETSAP (2010), ICF (2012), JRC (2013), EPA (2015) and Rutgers (2015).

All three of these are key to determining the variable OM costs and the total fuel costs for both conventional generation sources as well as the solution, as these costs are determined by the average number of hours the CHP plant is generating electricity (and heat), as well as the average price of fuel inputs and the average efficiency rate that were collected and used for evaluation in all electricity generation solutions models. Table 4 presents a comparison between combined heat and power plants; conventional electricity generation sources (*i.e*. coal, gas and oil) and diesel boilers.

Table 4 - Main financial and technical indicators used in the model for CHP units, conventional electricity generation sources and diesel boilers

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **Capital costs ($/kW)** | **Fixed OM costs ($/kW)** | **Variable OM costs ($/kWh)** | **Average Annual Use (kWh/kW/year)** | **Weighted Average Fuel Price ($/kWh)** | **Weighted Average Efficiency (%)** |
| **CHP Plants** | $1845 | $85,39 | $0.01 | 6856 | $0.043 | 41% (Electric Efficiency) |
| **Weighted average of Conventional Coal, Gas and Oil Plants** | $1923 | $32,95 | $0,004 | 4971 | $0.084 | 41% |
| **Diesel Boilers** | $77 | $19,89 | $0,0007 | 7946 | $0.098 | 75% |

### Climate Inputs

Climate outcomes were analyzed using a similar approach to the financial analysis. In order to calculate the climate impacts in our OPT scenario, in terms of maximum annual emissions reduction, total emissions reduction, and PPM equivalent, we CHP generation globally from 2014-2045 and then calculate the emissions reductions due to the replacement of conventional electricity generation sources and diesel boilers with CHP systems.

Our model analysis of the climate impacts of adoption in the OPT scenario is primarily derived from the direct emissions factor associated with the impact of this solution due to the replacement of conventional electricity generating technologies and diesel boilers with CHP. The other significant emissions are “local” due to the exhaust emissions in the CHP plants of dust, CO, NOx, SO2 and VOCs.

Indirect emissions are also accounted in the RRS model analysis. Several hundred life cycle assessments (LCAs) have been conducted for power technologies across the globe over the last 30 years (*e.g.* Pehnt et al., 2006; Masanet, *et al*., 2013). LCAs determine the environmental impacts of products and technologies throughout their full lifetime, from raw material extraction and processing; to manufacturing and distribution; to use and maintenance; to disposal or recycling. LCAs include estimates of total greenhouse gas (GHG) emissions and other environmental impacts and resources used (*e.g.* water and land use, air pollutants emissions). Despite the large number of papers addressing LCA for electricity generating technologies, indirect emissions estimates for CHP units are typically lacking. We considered the same indirect emissions as natural gas power plants reported in IPCC.

No data was also found for boilers, but these emissions are assumed to be small enough to not affect the overall system and were not accounted.

## General Assumptions

Six overarching assumptions have been made for Project Drawdown models to enable the development and integration of individual model solutions. These are that infrastructure required for solution is available and in-place, policies required are already in-place, no carbon price is modeled, all costs accrue at the level of agency modeled, improvements in technology are not modeled, and that first costs may change according to learning. Full details of core assumptions and methodology are available on the Project Drawdown Reduction and Replacement Solutions (RRS) Model Framework and Guide report. Beyond these core assumptions, there are other important assumptions made for the modeling of this specific solution. These are detailed below.

In creating the model and carrying out the analysis of co-generation as a climate change mitigation solution, a number of other assumptions have been made and are listed below.

1. Power generation from CHP generation is assumed to replace that from the electric grid and hence grid electricity usage minimizes or reduces to zero. Hence the emissions from power plants as in the situation of separate heat and power (SHP) generation is mitigated (accounted on CHP Electricity model).
2. Demand for heat for on-site operations which otherwise would have been provided by boilers as in the case of SHP is assumed to be provided by CHP systems (calculations under the CHP Heat model)
3. The CHP solution accounts for just those of gas turbine prime mover systems.

* The gas turbine is the most widely used prime mover for large scale CHP applications, such as those which would occur in the industrial sector. Furthermore, these systems are well documented and information about their characteristics is easily available.
* In the US, gas turbines account for 64% of installed CHP capacity (EPA, 2015). Globally they represent near 59% of CHP electricity generation (Greenpeace, 2015).

1. The price of fuels (oil, natural gas and electricity generation grid mix is assumed to remain constant over the period of analyses. This is because accurate forecast of fuel prices is very uncertain and difficult at best.
2. No efforts have been made to investigate the benefits of increased renewable energy adoption within industry on top of increased CHP usage. In any case, renewable energies which could be used to power industrial processes have been investigated elsewhere in the Project Drawdown under solutions such as Large Bio-Digesters, Biomass, and Waste to Energy.
3. A conservative approach is considered in the potential reductions from electricity grid replacement use, since the electricity transmission and distribution losses is not currently being accounted.
4. In the analysis, no learning rate is considered neither for the conventional technologies and for the solution since all are considered mature.
5. No financial revenues are considered due to potential electricity generation excess sold back to the grid.
6. To avoid double counting between the two models (Heat and Electricity), only the climate impacts, and net and lifetime operating savings are accounted from the CHP Electricity model.
7. The emission factor applied to all fuel (including electricity) use is that listed in the RSS core model as BAU grid emissions factors.

* The analysis of co-generation concentrates on the energy efficiency aspect of this solution and not its ability to appropriate renewable energies as fuel, assuming a constant grid mix does not impede the focus.

## Limitations / Further Development

The approach used in the analysis takes the view that CHP systems are first and foremost a replacement solution for on grid conventional generation and heat produced in boilers. Despite accounted in the models, changes in type of CHPs and in the adoption of natural gas might be considered very uncertain, since one could expect higher or lower rates of natural gas vs, renewable energy use to the combined heat and power production. Further development on the model should seek to account for projected increases in the adoption of renewable energy sources and other energy saving measures within the industrial sector.

Regional data on current CHP use in individual countries, especially those outside of the EU and North America, is difficult to obtain and oftentimes non-existent. For this reason, the analysis presented here has been limited to an overall global view supported byprojections from other sources. While the lack of regional analysis is indeed a limitation, the model used is constructed in such a way as to allow country specific data to be easily integrated if available. While increasing the amount of co-generation in any country would more than likely have financial and climate benefits, of greater interest is determining how such an increase should look alongside the implementation of other climate change mitigation actions specially affecting the grid emissions.

# Results

This section presents results for the impact that an OPT adoption scenario for onsite CHP technologies fueled by natural gas will have on emissions mitigation pathways and the required costs to achieve this.

## Adoption

In the OPT scenario, onsite CHP units’ role in electricity generation is assumed to increase from 3.2% (2014) to 6.24% of the total through the years 2020 to 2050 following our customized Conservative adoption case (see RRS model) for increased auto producers and natural gas use as prime mover. Correspondingly the thermal demand met by CHP increases from 1.7% to 2.9% in the same period.

The cumulative growth of CHP in both the OPT and BAU scenarios for 2014 to 2060 are demonstrated in Figures 6 and 7. If instead of the customized adoption cases, the existing prognostications option was chosen, in which the current shares of natural gas and auto-producers are kept constant, the results would be significantly lower. Under these scenarios the solution growth is only related to an increased use of CHP to meet global heat and electricity demand growth.

Figure 6: Adoption of CHP in the OPT and BAU scenario for heat production

Figure 7: Adoption of CHP in the OPT and BAU scenario for electricity generation

## Climate and Financial Impacts

The main results from the climate impact are shown below in Table 1. The combined climate change impact of increased adoption of onsite CHP auto-producers running on natural gas by 2050, indicates that this solution could reduce emissions by 4.07 billion tonnes (Gt) by 2050. This will drawdown global CO2 in the atmosphere by 0.39 ppm. The results in table 1 represent the difference in emissions between the OPT and BAU scenarios. The value given here for max annual emissions reduction is for the year of analysis 2050. The total electricity generation presented in 2050 for the OPT scenario of 2884 TWh represents a global installed capacity of 0.42 TW.

Table 1: The climate results of the analysis for CHP adoption

|  |  |  |  |
| --- | --- | --- | --- |
| **Max Annual Emissions Reduction** | **Total Emissions Reduction** | **Approximate PPM Equivalent** | **Approximate PPM rate of change from 2049 to3 2050** |
| 0.61 | 4.07 | 0.39 | 0.055 |
| Gt CO2 / yr | Gt CO2 (2020-2050) | ppm CO2-eq (2050) | ppm CO2-eq |

As is shown in Table 2, the implementation of CHP systems in the industrial, commercial and transport sectors deliver substantial savings over the 30-year period analyzed.

Increasing CHP auto-producers fueled by natural gas adoption from the current 3.18% to 6.24% of global electricity generation and from heat production from the 1.7% of total heat supply to 2.9% by 2050 is estimated to cost US$284 billion and US$8.6 billion in cumulative and marginal first costs respectively, according to the modeling results. This assumes an average installation costs at US$1845 a kilowatt (based on the meta-analysis of several data points) and O&M costs of $0.0118 cents/kWh. The net operating cost savings from the combined heat and electricity generation for 2020-2050 would be near US$417 due significantly to lower fuel use and costs over a business-as-usual scenario. When looked at over the full lifetime of CHP adoption from 2020-2050, lifetime savings in net present value (NPV) will be US$4.8. First and marginal costs are only considered from the heat model due to the replacement of conventional diesel boilers by CHP units. Operating savings are a sum of the results from both models.

Table 2: The financial results of the analysis for global CHP adoption

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Cumulative First Cost (Install/Implementation + Replacement)** | **Marginal First Cost (Install/Implementation + Replacement)** | **Net operating Savings** | **Lifetime Savings** | **Lifetime Savings NPV** |
| $ 284 | $ 8.6 | $ 417 | $ 3500 | $ 4.8 |
| Billion USD | Billion USD | Billion USD | Billion USD | Billion USD |

# Discussion

Co-generation has been proven to be a cost-effective method for providing electricity and heat to industrial, commercial and transport facilities consumers. What makes co-generation unique amongst energy saving strategies is its ability to fulfill both the power and heat demand of energy intensive systems while at the same time relieving stress upon electrical grid. This distributed functioning implies that production must be overseen by the end-user, and that they will incur the associated costs. However, as shown, CHP systems will likely reduce costs for end users. On the other hand, acknowledging that CHP is just one of several ways to invest in industrial processes to improve efficiency of energy use, the emissions reductions brought by this solution’s adoption benefit the whole of society.

Whilst some countries are achieving high share of CHP in their electricity production, through the use of effective policies and regulations, most countries have made less progress. There is therefore the need for further promoting the adoption CHP at the state, regional and global level.

The analysis undertaken has shown the financial and climate impacts of increased CHP adoption. The increased adoption came in the form of 81% increase in electricity generation from CHP units by the year 2050. This analysis highlight the energy efficiency aspect of CHP rather than its ability to utilize fuel supply from various renewable energy sources or to be integrated with district heating systems. Using only natural gas may be seen as an overly conservative approach in some respects as these other two aspects would surely augment the financial and climate benefits received. However, as the topics of district heating and renewable energy sources such as waste, wind, solar, and biomass are taken up elsewhere in Project Drawdown, it was appropriate to narrow the focus here to avoid double counting.

The analysis relied on several assumptions most of which had to do with future adoptions, fuel use and development of auto producers vs. main activity CHPs. It may be said that these assumptions stemmed from an adherence to the current state of energy use in industry, commercial and transport sectors in which the majority of energy produced by CHP systems comes from the combustion of natural gas and supported on future projected trends portrayed in Greenpeace results.

Despite these conservative leanings, the results of the analysis show a positive benefit in both climate and financial terms. The conclusion derived from this, and other similar analysis, is that CHP systems are well worth the investment and can play a significant part in emissions mitigation.

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1. This range excludes micro turbine and fuel cell based systems as these technologies are not as mature as gas and steam turbines and reciprocating engines. [↑](#footnote-ref-1)