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Impact of Co-firing Straw for Power Generation to Air Quality: A Case Study in Two Coal Power Plants in Vietnam

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Abstract. Open field burning of rice straw regularly contributes to severe air quality issues affecting millions of inhabitants in the city of Ha Noi. We examine how much replacing open field burning by co-firing mitigates local air pollutants and greenhouse gases emissions. We select two coal power plants located in the North of Vietnam as specific examples. Our findings show that co-firing straw in these plants at 5% mixing ratio on heat basis can reduce greenhouse gas emission as well as air pollutant emissions (SO₂, PM10 and NO_x) from 3% up to 13%. We examined the social value of these emission reductions using external costs factors. The health benefits of improving air quality by disposing of straw at a large coal power plant instead of open field burning are over ten million USD per year. This is the same order of magnitude as the technical costs of co-firing. Greenhouse gas emissions reduction benefits appear smaller.

1. Introduction

Vietnam's major crop is rice with annual production of 45 Mt in 2015 [1]. Rice straw and rice husk are the by-product of rice production. Residue to product ratio of rice straw is 1:1, which means that to produce 1 t of rice, there will be 1 t of straw [2], and implies that about 45 Mt of straw is produced every year in Vietnam. In the past, straw was used as cooking fuel, cattle feed or composted [3, 4]. Nowadays, with the development in rural areas, straw is less or no longer used for such purposes. It becomes a waste to be disposed of to free the land for the next crop.

The simplest and cheapest way for the farmer to manage the large amount of straw produced after harvesting is to burn it right in the paddy field. According to Nguyen (2012), 60 to 90% of the rice straw in the rice cultivation areas around Hanoi was burned in open fields, and greenhouse gases (GHG) emissions from open field burning of rice straw in Red River Delta caused an environmental damage equivalent to 19 to 200 million USD per year, depending on the social value of CO₂ [5]. Open field burning is an uncontrolled combustion process. It releases significant amounts of air pollutants beyond CO₂, such as CO, SO₂, NO_x and particulate matter (PM). These pollutants have negative impacts to local air quality and human health.

In our study, we look at co-firing technology as an alternative to uncontrolled in-field burning for rice straw disposal.

Co-firing generally means the combustion of two different fuel at the same time. Co-firing biomass such as wood chips, pellets, rice husk or straw is a cost-effective way to increase the renewable energy content of the power generation sector, thus mitigate greenhouse gas emissions. Specifically in this text, co-firing will refer to burning rice straw along with coal in a coal-fired power plant. For co-firing,



straw must be collected and transported from fields to the plant. At low mixing ratio (<10%), biomass can simply be ground to fine particles and mixed with coal to burn in the furnace without a costly retrofit of the plant. Burning one kilogram of straw does not generate as much heat as burning one kilogram of coal, but still the heat content of straw allows using less coal.

Co-firing straw with coal in coal power plants has many effects on emissions:

- The amount of straw burnt remains the same, but its energy is not wasted. It can partially substitute coal for electricity generation. Net greenhouse gases emissions are reduced by burning less coal.
- Co-firing reduces the amount of straw burned in open fields during harvesting season. A diffuse pollution problem is replaced by a point pollution problem. Then, pollutants can be treated by the plant's emission control systems.
- Typically, straw contains much less sulphur than the coal it replaces, hence reducing the SO₂ emissions.
- As a side benefit, a fraction of biomass can improve the combustion conditions at the plant and lower the quantity of some other pollutants generated from the coal itself.

In this study, we conduct a quantitative assessment of how co-firing rice straw improves local air quality as well as its CO₂ emissions mitigation. We add up the emissions at the power plant with the emissions in the fields and compute the emission reduction associated with co-firing.

2. Method

We consider direct co-firing at a biomass-mixing ratio of 5% on heat basis in two coal power plants. The old Ninh Binh coal power plant has a capacity of 100 MW. The new Mong Duong 1 coal power plant is ten times bigger with an installed capacity of 1080 MW. Both are located in the north of Vietnam, within the Red River Delta where open field burning contributes to serious air quality issues affecting the lives of millions of people every year.

We estimate the emissions of four pollutants: particulate matter (PM₁₀), SO₂, NO_x and greenhouse gases (GHG).

The system boundary for study includes three segments: (1) straw/coal combustion in plants, (2) straw/coal transportation and (3) straw burned in the open field. We assumed that the rice production and coal mining remain the same with or without co-firing. Table list the input parameters for emission calculation.

Table 1. Input parameters for emission calculation

	Mong Duong 1	Ninh Binh
Coal consumption (Mt/y)	2.71	0.43
Coal transport distance (km)	0	200
Straw required for co-firing (kt/y)	226	40
Transportation activity (Mt-km)	19.27	0.53
Straw collection radius (km)	68	14
ESP efficiency	99.6%	99.2%
Desulphurization efficiency	98.2%	N/A

In the baseline, there is no straw co-fired in the two power plants. Emissions come only from coal combustion, coal transportation and open field burning of the straw produced in the provinces around the plant.

For the combustion activities, emission is calculated by Equation (1) with the emission factor of each pollutant for coal and straw shown in Table . Emission control systems in the power plants can filter some pollutants. Thus, we consider the efficiency (η) of such system in our calculation. For the pollutants emitted without any control measure, the efficiency is zero.

$$Emission_{pollutant} = \sum_{fuel} Quantity_{fuel} \times Emission\ Factor_{fuel,pollutant} \times (1 - \eta_{control\ system}) \quad (1)$$

Emission for transportation activities is calculated by Equation (2) using emission factors listed in Table 2, and the activity levels (in t·km) estimated as follows. Coal is supplied to Mong Duong 1 by conveyor belt from the coalmine nearby. Since the transport distance is small, we assume that the emission from coal transportation by conveyor belt is negligible. Ninh Binh gets its coal supply by barge through 200 km distance. We assume that straw is delivered to the plants by 20 t unit load trucks.

$$Emission_{pollutant,transport\ mode} = Transport\ activities \times Emission\ factor_{pollutant,transport\ mode} \quad (2)$$

We converted the emission reduction quantities into monetary values using external costs factors. We estimate the benefit from CO₂ emission reduction by using a carbon price derived by international comparisons. From the health benefits of local air quality improvement, we used a range of three studies [6]–[8] as shown in Table 3 in order to deal with the deep uncertainty regarding these cost factors.

The Appendix tabulates the numerical values of the main engineering and economic parameters. Complete data and code of the system model developed by the authors [9] is available for download on Github.

Table 2. Emission factors

		CO ₂	SO ₂	PM10	NO _x
Fuel combustion (kg/t of fuel)	<i>Coal-Mong Duong 1</i> [14]	1 877	11.5	43.8	18
	<i>Coal-Ninh Binh</i> [14]	2 081	11.5	26.1	18
	<i>Straw</i> [15]	1 004	0.18	9.1	2.28
Transport mode (g/t/km)	<i>Conveyor belt</i>	0	0	0	0
	<i>Road</i> [16, 17]	110	1.5 10 ⁻⁴	2 10 ⁻⁴	0.134
	<i>Barge</i> [18]	71	1.6 10 ⁻²	2.6 10 ⁻³	0.4

Table 3. Social cost of air pollutant emissions (USD/t of emitted pollutant)

Pollutant	External cost factors [6]	Health damage cost [7]	Health damage cost [8]
SO ₂	3 680	3 767	1 134
PM10	2 625	5 883	2 496
NO _x	2 438	286	1 398

3. Results

Figure 1 summarizes results on emissions estimation. There are four dimensions: at each plant, we represent the emission of each pollutant, from three activities, comparing two scenarios: baseline and co-firing. These dimensions are arranged as follows. The left panel shows emission from Mong Duong 1 case, the right panel shows emissions from Ninh Binh case. Vertically, each of the four stacked bar pairs corresponds to one pollutant. Within the pair, the top bar represents emissions with co-firing, the bottom bar the baseline emissions. In all of the eight pairs, the emissions are lower with co-firing than the baseline. This result shows that co-firing reduces emissions of all pollutants considered, in both plants.

The horizontal axes represent the quantity of pollution emitted in one year. In absolute terms, Mong Duong 1 is larger and pollute more, so its scale at the top goes to 60 kt/y compared to Ninh Binh's 9 kt/y. Relative to the quantity of electricity produced, Mong Duong 1 is less polluting, but that is besides the discussion here.

Local air pollutants emissions (SO₂, PM10 and NO_x) are plotted against the top axis and GHG emission is plotted against the bottom axis. These scales differ since GHG emission is higher than local air pollutants emission by three order of magnitude. GHG emission reduction will be much higher than NO_x and PM10 emission reduction in absolute mass.

Total length of the bar represents the total emissions, adding up the three segments of the system. Co-firing straw with coal at 5% at Mong Duong 1 could save 249 423 tCO₂eq per year (see Table). This number is 44 788 tCO₂eq per year for Ninh Binh. In percentage compared to baseline, PM10 has the highest relative emission reduction. Although it has the smallest reduction in t per year, SO₂ reduction is the second highest in term of percentage (Table).

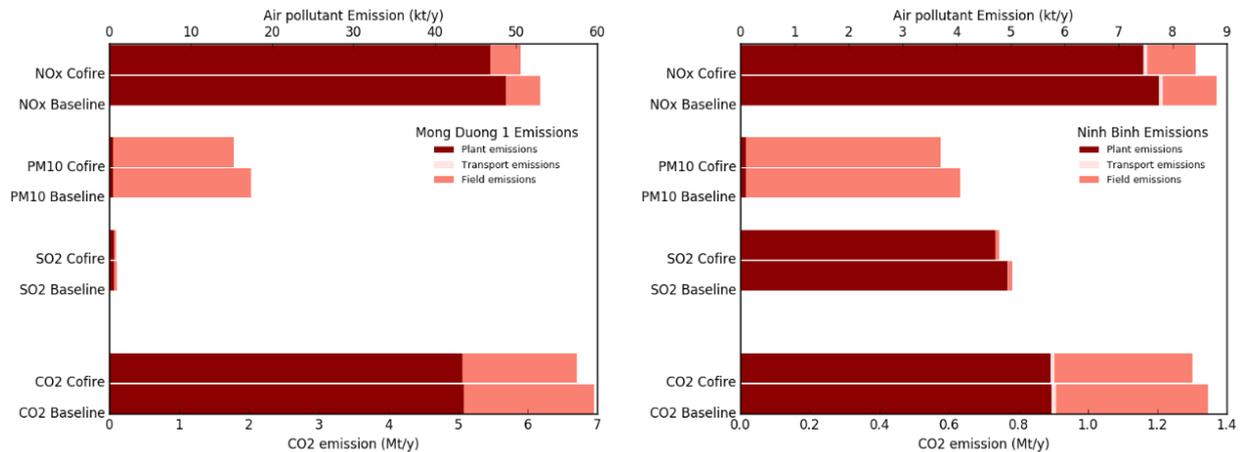


Figure 1. Co-firing reduces emissions compared to baseline in the two power plants. Mong Duong 1 is left, Ninh Binh is right. Ninh Binh plant emits less CO₂ than Mong Duong 1 plant because it is ten times smaller. However, its SO₂ emissions are larger because it lacks a desulphurization system. The PM10 emissions mostly come from open-field burning because plants have dust filters and precipitators.

Comparing left and right plots on Figure 1 shows that the benefits of co-firing depend mainly on the characteristics of the plant: size, existence of pollutant controls. When the plant has pollutant control technologies, the related pollutant emission from combustion activity in the plant is reduced significantly. With both ESP and desulfurization system, PM10 and SO₂ emission from Mong Duong 1 power plant is negligible compared to CO₂ and NO_x emission. For Ninh Binh, ESP system also filtered PM10 emission significantly. Combustion in power plant accounts for the majority of NO_x emissions in both plants since there is no NO_x control measure installed.

Since there is no emission control measure in both power plants, the combustion of straw in co-firing only has a very slight effect on emission reduction of GHG and NO_x due to the lower emission factor of straw compared to coal. Instead, emission reduction mostly comes from the amount of coal saved from burning in the plant by co-firing for these pollutants. Emission reductions of SO₂ and PM10 in Mong Duong 1 (and only PM10 in case of Ninh Binh) reflect the amount of coal consumption reduced in plants and the effect of emission control technologies deployed in the plants.

Table 4 summarizes emission reductions of each pollutant by activities. For both studied plants, emission from transportation is negligible and not visible in Figure 1, except for GHG emissions from Ninh Binh. However, we find that for Mong Duong 1, biomass transportation increases GHG and air pollutants compared to the baseline case. Mong Duong 1 is located next to a coalmine and coal is delivered by conveyor belt, so coal transportation activity is assumed to be zero. While coal is supplied from a nearby mine, biomass is collected and transported with a collection radius of 68 km. With a capacity ten times larger than Ninh Binh, biomass transportation activity is 19.27 million t·km, which adds 2 172 tCO₂eq per year to the total emission. For Ninh Binh, straw is collected and transported locally while coal is transported from a coalmine 200 km away. Thus, the transportation activity in the co-firing case emits 546 tCO₂eq less than the baseline case.

Emissions from the plant's stack are much larger than emissions from the field for the pollutants that are emitted without control measures (GHG and NO_x in case of Mong Duong 1; GHG, NO_x and SO₂ in case of

Ninh Binh). PM10 and GHG account for the largest part of emissions from open field combustion of rice straw.

Combustion activity in power plant contribute most to emission reduction of the pollutants that not controlled by any measure. For example, NO_x emission reduction is largest from plant combustion in both plant. SO₂ emission reductions also mostly comes from plant combustion activity in Ninh Binh case. This reflects the effect of replacing part of coal in the plants by straw, which has emission factor of SO₂ 60 times lower than that of coal and emission factor of NO_x 8 times lower.

Table 4. Emission reductions by activities (t/y)

Plant	Activity	GHG	SO ₂	PM10	NO _x
Mong Duong 1	<i>Plant combustion</i>	25 599	27	15	1 899
	<i>Transportation</i>	-2 172	0	0	-3
	<i>Field combustion</i>	225 996	41	2049	513
Ninh Binh	<i>Plant combustion</i>	4 416	237	2	292
	<i>Transportation</i>	546	0.1	0.2	3
	<i>Field combustion</i>	39 827	7	361	90

The benefit of GHG emission reduction is estimated using social carbon value. Carbon pricing policy for electricity production is not yet in place for Vietnam. We looked at “State and trends of carbon pricing” [10], a review of existing carbon pricing instruments in other countries, to choose a social carbon value for our analysis. Kossoy et al.’s [10] observe a wide range of carbon prices from 1 to 130 USD/tCO₂e. However, 99 % of emission are priced less than 30 USD/tCO₂e and 85% are priced less than 10 USD/tCO₂e. We have plotted the carbon prices of all countries listed in the mentioned report against their Gross Domestic Production (GDP) per capita to see in which range that carbon value for Vietnam could fall in (see Figure 2). Vietnam GDP per capita is much lower than the lowest income countries that present in the list, which is China. China has carbon tax rate at 5 USD/tCO₂e and has the 2014 GDP per capita at 7 590 USD while the GDP per capita for Vietnam is only 2 052 USD. For this reason, we choose the lower bound of the observed range. The social carbon value used to estimate the benefit from GHG emission reduction in this study is 1 USD/tCO₂eq. Considering a social carbon value at 1 USD/tCO₂eq, the environmental benefits from greenhouse gas emission reduction of co-firing for Mong Duong 1 is 250 kUSD/year and for Ninh Binh is 45 kUSD/year.

Table 5. Emission reductions and associated benefits for two plants

Pollutant	Mong Duong 1			Ninh Binh		
	Emission reduction (t/y)	Emission reduction (%)	Benefit (kUSD/y)	Emission reductions (t/y)	Emission reduction (%)	Benefits (kUSD/y)
GHG	249 423	3.7%	249	44 788	3.4%	45
SO ₂	68	8%	77-256	244	4.9%	277 - 921
PM10	2 063	13.4%	5 149-12 141	362	9.8%	904-2 133
NO _x	2 409	4.6%	689 – 5 873	382	4.4%	109-931

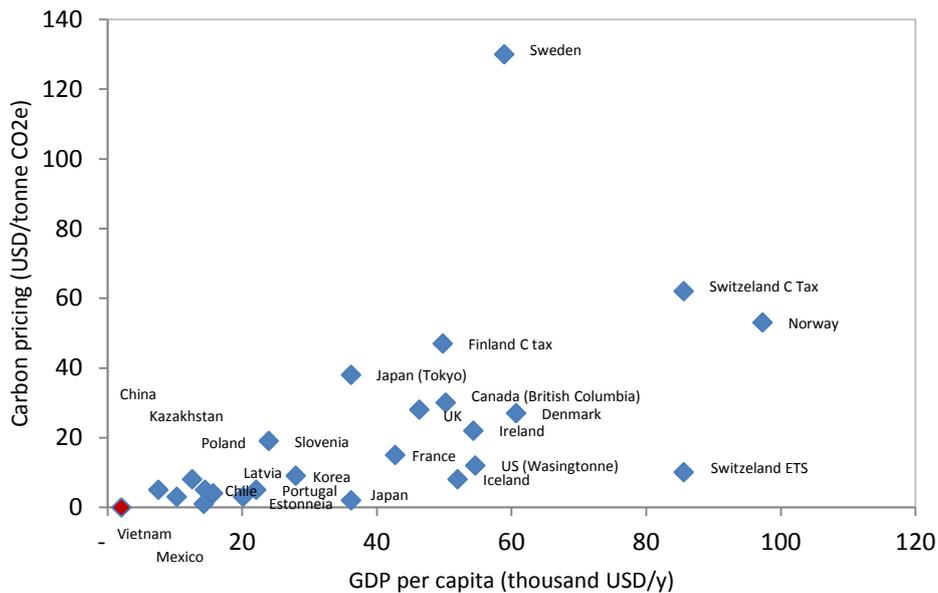


Figure 2. Carbon pricing policy against countries' GDP. Carbon pricing policy for electricity production is not yet in place for Vietnam. Vietnam GDP per capita is much lower than the lowest income countries that have carbon pricing policy, which is China.

We use health damage cost specified for each air pollutant to monetize the impact of emission reduction to public health. We refer to the health damage costs used to estimate health impact in other neighbour countries such as Thailand and China in previous studies. Although these values vary between countries, the health impact from PM10 emissions remain the highest.

Health benefit from reducing air pollution emission is 8.6 - 13.3 million USD per year for Mong Duong 1 and 1.7 - 3.2 million USD per year for Ninh Binh. The majority of health benefit comes from PM10 emission reduction. This is because PM10 has the highest social cost as seen in

Table 3.

Benefit of air pollutant mitigation does not proportionate to the size of the coal power plant. SO₂ emission reduction in Mong Duong 1 is much smaller compare to Ninh Binh despite that it is 10 times larger in capacity. As a result, the benefit from SO₂ emission reduction is higher in Ninh Binh case. This is because with high efficiency desulphurization system, the emission from coal combustion is significantly reduced even without co-firing. Thus, for co-firing scenario, the substitution of coal by straw has less impact compare to Ninh Binh case.

4. Discussion

Co-firing rice straw with coal in coal power plants reduces local air pollutants emissions by two effects. First, the substitution of coal by straw lowers the air-borne pollutants emission at the plant because straw has lower emission factors than coal. Second, co-firing reduces the amount of straw burned in the open field. Instead, straw will be burned in coal boiler and the emission will be reduced by plant's filtering systems such as electrostatic precipitation, desulfurization system.

Co-firing straw offers a measure to reduce greenhouse gas and air pollutant emissions. Air pollutant emission reductions depend control technologies deployed by the power plants. In the baseline case, the amount of straw required for co-firing is open burned without any emission control measure. In the co-firing case, when straw is combusted in the plant's boiler, pollutants such as PM10 and SO₂ are filtered. The technologies for air pollutant control in power plants (such as electrostatic precipitator, DeNO_x and DeSO₂) are commercially available. This is not the case for CO₂ emission control technology. Carbon capture and storage (CCS) is the technology of capturing the CO₂ produced by a power plant in order to inject it into deep geological formations. CCS is not yet considered in the latest

National Power Development Plan of Vietnam [11]. Cost of technology is one of the main barrier since it would increase the cost of electricity produced by coal power plants to a point where they may be uncompetitive with other generation technologies [12]. In the long run however, biomass energy with CCS has been proposed as a technologically plausible way to extract CO₂ from the atmosphere. Co-firing is a step in this direction.

Co-firing rice straw for heat and power generation already exist in other countries such as China and the US. It is known to work, however there are technical and economic difficulties. Rice straw is a scattered resource, which requires work for collection and transportation. Mobilizing large amount of straw for co-firing in large coal power plants imposes additional cost to the plants. Technical costs for retrofitting coal power plants for co-firing includes investment cost, fuel cost and operation and maintenance cost. The costs for retrofitting coal power plants for co-firing with co-feed, the simplest and cheapest co-firing technology, ranges from 300 to 700 USD/kW [13]. Operation and maintenance cost is about 2.5 to 3.5% of capital cost. Fuel cost depends greatly on the origin, type and composition of biomass feedstock. Since the costs of co-firing are concentrated and private, while its benefits are diffuse and public, co-firing raises interesting political economy problems.

There are alternatives to open field burning for disposal of rice straw. Making rice straw pellets is one option. Rice straw pellets are a better fuel and technically more suitable for co-firing than raw rice straw since pellets have a higher heating value, higher grind ability and are easier to transport and to store. However, it is difficult to produce pellet form rice straw, compared to other types of biomass. Additives are usually required. Costs of pelletizing imply that using raw straw is cheaper for power plants co-firing at a large scale. Pellets appear more economical for small-scale applications such as small boiler for heat production or cook stove.

A central result of our numerical analysis is that benefit from GHG emission reduction are small compared to health benefits. Lacking estimates in the Vietnamese context, we used a range of international studies for external costs factors of local air pollution. Regarding the value of GHG emission mitigation, we believe the 1 \$/tCO₂ carbon value used is appropriate in a low middle-income country like Vietnam. This value could increase if there were effective international clean development mechanisms. There is a Joint Crediting Mechanism (JCM), a bilateral carbon credits trading scheme between Vietnam and Japan. GHG benefits of co-firing could also increase if Vietnam implements a carbon market –it is expected that the legal framework for carbon market should be set up by 2020– or renewable energy portfolio standards in the power sector.

5. Conclusion

Co-firing reduces GHG emissions by replacing coal, and it reduces pollutant emissions detrimental to local air quality caused by open-field burning. Our study quantified these benefits in the context of Vietnam today. We find that the local air improvement is more important than GHG mitigation in terms of social value. Co-firing straw has large positive impact on public health: we estimate the social value of avoided air pollution at –around ten million USD per year for the large plant and – two million USD per year for the smaller plant. The largest part of these benefits comes from reducing the PM10 emissions. Co-firing straw with coal in power plants would improve Hanoi air quality.

In our future work, we will extend our research to include all the operating coal power plants in the North of Vietnam to assess fully the impact of co-firing to air pollutant and greenhouse gas mitigation in Red River Delta region.

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