Supplementary material to Economics of co-firing rice straw in coal power plants in Vietnam

Model documentation

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1. Introduction

This note documents an empirical model of the rice straw cofiring sector. It is an implementation of the theoretical equations described in the manuscript *Economics of co-firing rice straw in coal power plants in Vietnam*.

This note is organized as follows. Section 2 exposes in pseudocode how the costs are derived from the technical parameters. Since the prices are all exogenous, we only focus on how the quantities are derived. For the quantity of coal used at the power plant, we consider an *ex ante* situation without cofiring and a *ex post* situation with cofiring. Section 3 derives the quantities of work needed to harvest and transport the straw. They depend on integral calculus which is solved exactly using geometrical assumptions. Section 4 provides details on the code. Finally, section 5 lists the numerical value of parameters (Table A1). They were obtained from the source cited in the list of references, completed for plant's parameters by interview of plant's personnel. We used an exchange rate of 1 USD = 22 270 VND to convert prices from the international literature.

2. Model equations

Quantity of coal used, without cofiring:

power_generation = capacity * capacity_factor

Q^{o}_{coal} = *power_generation* / plant_efficiency / coal.heat_value

Quantity of coal used, with cofiring:

boiler_efficiency_loss(*r*) =0.0044 * *r* * *r* + 0.0055 * *r*

derating = 1 – boiler_efficiency_loss(cofire_rate * coal.heat_value / biomass.heat_value) / boiler_efficiency_new

gross_heat_input = capacity * capacity_factor / plant_efficiency / *derating*

Q_{coal} = (1 – cofire_rate) / coal.heat_value * *gross_heat_input*

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Quantity of biomass used with cofiring:

Q = cofire_rate / biomass.heat_value * *gross_heat_input*

Investment cost to install the biomass cofiring equipment:

C_{inv} = investment_cost * capacity * cofire_rate

Operating and maintenance costs, without cofiring:

C^{o}_{OM} = fix_om_coal * capacity + var_om_coal * *power_generation*

Operating and maintenance costs, with cofiring:

C_{OM} = (1 – cofire_rate) * C^{o}_{OM} + cofire_rate * (fix_om_biomass * capacity + var_om_biomass * *power_generation*)

The reseller performs two tasks, loading and driving the trucks. For each task, there are three costs components, which are labor, fuel and capital:

loading_work = truck_loading_speed * Q

transport_tkm = … ### Integral calculus explained below ###

driving_work = *transport_tkm* / truck_load / truck_velocity

labor_cost = wage_bm_transport * *driving_work* + wage_bm_loading * *loading_work*

fuel_cost = fuel_cost_per_hour_driving * *driving_work* + fuel_cost_per_hour_loading * *loading_work*

rental_cost = rental_cost_per_hour * (*loading_work* + *driving_work*)

$C_{reseller}$ = *labor_cost* + *fuel_cost* + *rental_cost*

The costs to collect the biomass has the same three components:

labor = Q / winder_haul * work_hour_day

labor_cost = wage_bm_collect * *labor*

fuel_cost = fuel_cost_per_hour * *labor*

winder_use_area = … ### Integral calculus explained below ###

rental_cost = winder_rental_cost * *winder_use_area*

$C_{collect}$ = *labor_cost* + *rental_cost* + *fuel_cost*

We compute the emissions reductions system-wide. For any activity a, the emissions of pollutant p are estimated as the product of its level by its specific emission factor $ef(p, a)$, net of eventual emission controls. The emissions factors values are given the manuscript (table 4). To obtain system-wide emissions, we sum across all polluting activities a so that:

$$E_p = \sum_a ef(p,a) * level(a) * (1 - control(p,a))$$

The power plant segment has two polluting activities: burning coal and burning biomass. The level of the coal burning activity is measured by the coal mass, that is Q^{o}_{coal} tons without cofiring and Q_{coal} tons with cofiring. The level of biomass (straw) burning activity at the boiler is Q.

The farmers segment has two polluting activites: open field straw burning, and using a diesel winder to collect straw. Cofiring reduces the level of open-field straw burning by Q tons. The mass of diesel used to collect the straw is given by:

winder_use = fuel_use / winder_haul * Q

The reseller segment has just one polluting activity, road transport. Its activity level is *transport_tkm* defined below.

3. Geometrical assumptions for logistics.

The cost incurring to the straw reseller $C_{transport}$ is the sum of three terms: labour, capital and fuel costs. Each term depends linearly on the level of two activities: handling and transport. For example, the labour for driving is the transport activity level in *t km* divided by unit truck capacity in *t* and by average truck speed in *km/h*. Estimating the handling activity is simple, it is the quantity of biomass handled Q, in *t*. More sophisticated integral calculus is called for to determine the transport activity level.

We model collection zones in which biomass have uniform economic and physical characteristics. Let D note the density of biomass available in t/km^2 in a zone. To estimate it, we assumed that the attributes of a zone are those of a province. The province is not only the most convenient statistical unit; it is also a relevant scale to zone biomass collection logistics. We estimated the available straw density as follows:

Equation 1 $$D = Y \times F_{rice} \times F_{collected} \times F_{sold}$$

Where Y is the straw yield in $t/km^2 \cdot year$ of planted field, F_{rice} is the ratio of rice growing area over total province area, $F_{collected}$ is the percentage of straw collected and F_{sold} is the selling proportion. $F_{collected}$ and F_{sold} are 0.82 and 0.79 according to [12]. The straw yield is estimated based on the crop production [13], and the residue over product ratio, 1 kg of straw for 1 kg of paddy.

In the simplest case, biomass collection is one zone, a radius R disk centered on the plant:

Equation 2 $$Q = D \times \pi \times R^2$$

Consider a unit area located at the distance r of the plant. Trucks do not travel in a straight line but take tortuous roads, so the distance driven from the area to the plant is $\tau \times r$ where τ is a tortuosity factor. We assume $\tau = 1.5$ following Diep [14] study on straw logistics in Vietnam. By definition, the activity to transport the biomass from that area to the plant is $D \times \tau \times r$.

Consider now all the area located between r and $r + dr$ of the plant. The length of the annulus is $2\pi \times r$, its infinitesimal width is dr, so the biomass quantity is $D \times 2\pi r \times dr$. The transportation activity to move it to the plant is $D \times 2\pi \times r \times dr \times \tau \times r$. We sum this expression from $r = 0$ to $r = R$ to obtain the transport activity for the whole disc:

Equation 3 $$Activity_{transport} = \int_0^R D \times 2\pi \times \tau \times r^2 \, dr = \frac{2\pi}{3} \times D \times \tau \times R^3$$

Equation 2 implies that the collection zone to supply the required amount of biomass has to extend as far as $R = \sqrt{\frac{Q}{\pi D}}$, therefore:

Equation 4 $$Activity_{transport} = \frac{2}{3} \times \tau \times \sqrt{\frac{Q^3}{\pi D}}$$

The disk geometry models the Ninh Binh case. However, Mong Duong 1 plant is close to the coastline, so a half-disk represents better its collection area. Moreover, the large amount of biomass will come from more than one province, and the province close to the plant has different agricultural characteristics than the provinces around it, so we model two different collection zones.

In the more general geometry, biomass comes from two non-overlapping semi annuli zones centered on the plant (Figure A1).

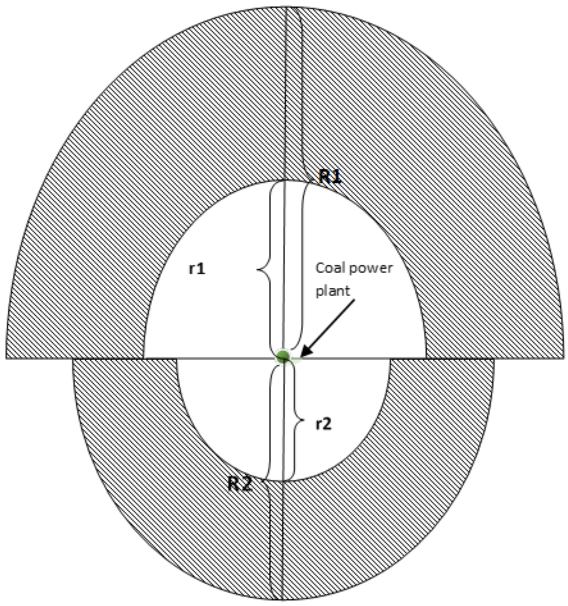

Figure A1. Geometric model of the straw collection area. The simplest circular geometry obtains when $R_1 = R_2$ and $r_1 = r_2 = 0$. The two concentric non-overlapping semi annulus case has $r_2 = 0$ and $r_1 = R_2$

Noting D_i the available biomass density in zone i, the quantity collected there is proportional to the zone area:

Equation 5 $$Q_i = D_i \frac{\pi \left(R_i^2 - r_i^2 \right)}{2}$$

This can be derived from Equation 2 by geometrical consideration: a semi annulus is obtained by subtracting the small inner disk from the large one, and taking half. The same argument with Equation 3 gives the transportation activity:

Equation 6 $$Activity_{transport\ zone\ i} = \frac{\pi}{3} \times D_i \times \tau \times \left(R_i^3 - r_i^3 \right)$$

In the empirical model of the Mong Duong 1 case, $r_2 = 0$ and $R_2 = r_1 = 50\,km$, the first zone is the province in which the plant is located. All the biomass collected from this zone is not enough, so the model computes how far the collection should reach, finding $R_1 = 72{,}9\,km$.

4. Implementation

The above equations are implemented in *Python 3*, using an object-oriented approach. In the central case, results in the manuscripts are presented in the simplest case: investment occurs in year 0, then assuming a steady-state for 10 years, no discounting and no residual value. But the model is features-full.

All the variables above are vectors with one element per year, the model allows for a variable time horizon, and financial calculations use prices, discounting, taxes and amortizations. These features allow sensitivity analysis to confirm the robustness of the key results shown in the central case.

We ensured code quality by using state of the art scientific software engineering practices, namely:

- *Makefile* to manage runs in a virtual environment; using *git* for version control;
- Self-testing with *assert* statements;
- Unit testing with *doctest* comments in the code;
- Regression testing with the *pytest* suite;
- Enforced compliance with Python code conventions with *black* code formatter and *pycodestyle* (aka pep8) verification before each commit;
- Enforced compliance with Python in-code documentation with *pydocstyle* (aka pep257) verification before each commit;
- Enforced static code analysis quality with *pylint* verification before each commit.
- We used the *natu* package to ensure that all formulas are dimensionally correct.

We found that using a general programming environment allowed to produce higher quality code than could be done in a spreadsheet. We reproduce all results tables and figures with one command. To report the main painpoints of our experience: The Python langage lacks a standard solution to handle units. We found it difficult to integrate Spyder, makefile, virtual environment and the python module system. Static code and regression analysis before commit takes a suprisingly long time considering the code size. The object oriented code is not concise, compared to the list of equations shown above.

The full code and parameters is available on GitHub under the project name AnHaTruong/Costs-and-Benefits-Cofiring-VN. It is licensed for reuse by all under the Creative Commons Attribution-Sharealike International 4.0 conditions.

5. Parameters

Table A1. Parameters of the cost-benefit analysis. Technical specifications of the plants, Straw supply chain, and financial assumptions

Parameter	New plant, like Mong Duong 1	Old plant, like Ninh Binh
capacity	1080 MW	100 MW
commissioning	2015	1974
boiler_technology	CFB	PC
capacity_factor	0.6	0.64
plant_efficiency (HHV)	0.3884	0.2177
boiler_efficiency_new	0.8703	0.8161
fix_om_main	29.31 USD/(kW*y)	29.31 USD/(kW*y)
variable_om_main	0.0048 USD/kWh	0.0048 USD/kWh
emission_control_CO2	0	0
emission_control_SO2	0.982	0
emission_control_NOx	0	0
emission_control_PM2.5	0.996	0.992
fuel_name	6b_coal	4b_coal
fuel_heat_value	19.4347 MJ/kg	21.5476 MJ/kg
fuel_transport_distance	0 km	200 km
fuel_transport_mean	conveyor_belt	barge_transport
derating[1]	1.0, 0.999440	1.0, 0.999334,
amount_invested	2.7 MUSD	0.5 MUSD
investment_cost[2]	50 USD/kW	100 USD/kW
fix_om_cost[2]	32.24 USD/(kW*y)	32.24 USD/(kW*y)
variable_om_cost[2]	0.006 USD/kWh	0.006 USD/kWh
OM_hour_MWh[3]	0.12 hr/MWh	0.12 hr/MWh
wage_operation_maintenance[4]	2.7 USD/hr	2.7 USD/hr
cofire_rate	0.05	0.05
cofuel_name	straw_boiler	straw_boiler
cofuel_heat_value	11.7 MJ/kg	11.7 MJ/kg
cofuel_transport_distance	Endogenous	Endogenous
cofuel_transport_mean	road_transport	road_transport
boiler_efficiency_loss	0.0044 r^2 + 0.0055 r	0.0044 r^2 + 0.0055 r
winder_rental_cost	40 USD/ha	40 USD/ha
winder_haul	6.57 t/d	6.57 t/d
work_hour_day	0.333333	0.333333
wage_bm_collect[5]	3.7 USD/hr	3.7 USD/hr
fuel_cost_per_hour	0.5 USD/hr	0.5 USD/hr
open_burn_rate	0.6	0.6
fuel_use	4.16 kg/d	4.16 kg/d
profit	1054 USD/ha	1054 USD/ha
barge_fuel_consumption[6]	8 g/(km*t)	8 g/(km*t)
truck_loading_time [7]	0.045 hr/t	0.045 hr/t
wage_bm_loading	1.11 USD/hr	1.11 USD/hr
truck_load	20 t	20 t
truck_velocity	45 kph	45 kph

Parameter	New plant, like Mong Duong 1	Old plant, like Ninh Binh
fuel_cost_per_hour_driving	7.15 USD/hr	7.15 USD/hr
fuel_cost_per_hour_loading	0 USD/hr	0 USD/hr
rental_cost_per_hour	9.62 USD/hr	9.62 USD/hr
wage_bm_transport[8]	2.13 USD/hr	2.13 USD/hr
productivity_surface[9]	8.04 t/hr	8.04 t/hr
productivity_underground[9]	2.5 t/hr	2.5 t/hr
wage_mining[10]	5.59 USD/hr	5.59 USD/hr
Coal [11]	50.8038 USD/t	81.9816 USD/t
electricity[11]	0.055643 USD/kWh	0.0747912 USD/kWh

Sources: [1] [1], [2] [2], [3] [3], [4] [4], [5] [5], [6] [6], [7] [7], [8] [8], [9] [9], [10] [10], [11] [11]

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