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# THE PRODUCTIVITY EFFECT OF PUBLIC-PRIVATE PARTNERSHIP

VINCENZO MOLLISI

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# The Productivity Effect of Public-Private Partnership

Vincenzo Mollisi*

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**Abstract**

Public authorities have increasingly resorted to public-private partnership (PPP) arrangements for the delivery of public services. A PPP bundles the construction, management, and maintenance of a facility in a unique contract. Using data from the Italian district heating industry, I find that PPP internalizes the technological externality between construction and operation tasks of a project by inducing a higher level of capital quality. A unit increase in the capital quality raises the output of PPP firms by 17%.

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*University of Mannheim and University of Turin, email: vincenzo.mollisi@gmail.com. I wish to thank Klenio Barbosa, Marco Buso, Giacomo Calzolari, Francesco DeCarolis, Leonardo M. Giuffrida, Daniel J. Grodzicki, Elisabetta Iossa, Martin Paldam, Ariel Pakes, Giulia Pavan, Andrea Pozzi, Gabriele Rovigatti, Philippe Schröder, Valerie Smeets, Frederic Warzynski and the participants in seminars where preliminary versions of this study were presented. All remaining errors are mine.

# 1 Introduction

In the last two decades, public authorities have increasingly resorted to public-private partnership (PPP) arrangements for the construction and operation of public utility infrastructures like highways, energy facilities or public lighting. A PPP compels a building and a facility-management company to participate in a consortium by creating a new legal entity, a special purpose vehicle (SPV). The bundling of multiple tasks into a single contract is the essence of a PPP procurement and is what differentiates it from traditional procurement, where the construction and operation tasks are regulated separately. This paper aims to understand both the economic rationalization for these arrangements and their effects on facility-management firms' efficiency, with an emphasis on the context of network utilities. Through the bundling, a PPP solves the typical moral hazard problem of separated sequential procurements. When the capital quality of the facility is non-contractible, the building company has a strong incentive to provide suboptimal levels of this input. As a consequence, the operating firm has to use a lower-in-quality input in its production function. This problem is pervasive in procurement settings as discussed by Albano et al. (2006), Decarolis (2014; 2018), Conley and Decarolis (2016), and Lopomo et al. (2021).

My paper shows the effects of incentivizing contracts in the realm of PPP. In this regard, Hart (2003), Bennett and Iossa (2006), Martimort and Pouyet (2008) and Iossa and Martimort (2015) isolate conditions for bundling to be optimal in presence of a technological externality across tasks. When the externality across tasks is strong enough to offset the cost of its own internalization, these studies show that bundling induces the contractors to look at the long-term performance of the asset (the "whole-life asset management" concept). This, in turn, bolsters the contractors' incentives to invest in asset quality. Martimort and Pouyet (2008) provide an example through the case of American circular prisons. The particular design of these buildings facilitates the work of prison officers by reducing the amount of work required to control prisoners. The existence of a positive (negative) externality implies that improving the capital quality reduces (increases) the firm's marginal cost at the operation stage. However, the lack of empirical evidence documenting the efficiency impact of PPPs and the results of many case studies that do not find clear evidence of management cost reductions or service quality improvements made the PPP the most debated instrument of the last ten years[1]. For most of the projects audited, there was no comparative analysis to demonstrate that a PPP offered the best value-for-money or to protect the public interest by ensuring full evaluation of the different procurement methods[2]. Besides, firms are entitled to local monopolist rights for some services of public utility. Thus any comparison of firms' performances that does not employ a price-neutral measure is not meaningful. Saussier et al. (2009) suggest that analyzing the relative efficiency of PPPs is not easy. Indeed, a serious comparative analysis must consider that observed efficiency is conditional on the preceding organizational choice and which kind of efficiency we want to measure. This paper evaluates PPP's applicability based on a suitable pool of observed data and the use of technical productivity as a comparable metric of firms' results.

This paper shows the effectiveness of contractual forms in mitigating the moral hazard problem. To implement the analysis, I exploit the fact that the operating firms do not directly decide the choice of the procurement scheme, and being a PPP or not is an exogenous treatment for firms. I use a structural production function model to separate the impact of the ex-ante non-contractible capital quality on output from other firm's unobservables. A control function approach is meant to retrieve a reliable proxy for the unobserved productiv-

[1] In this regard, the European Court of Auditors, see (European Court of Auditors (2018)), found that the European PPPs did not guarantee an adequate balance between benefits and costs: «we found that despite PPPs have the potential to achieve faster policy implementation and ensure good maintenance standards, the audited projects were not always effectively managed and did not provide adequate value for money. Potential benefits of PPPs were often not achieved, as they suffered delays, cost increases and were under-used, and resulted in 1.5 billion euro ineffective spending, out of which 0.4 billion euro EU funds. This was also due to the lack of adequate analyses, strategic approaches towards the use of PPPs and institutional and legal frameworks. With only few member states having consolidated experience and expertise in implementing successful PPP projects, there is a high risk that PPPs will not contribute to the expected extent to the aim to implement greater part of EU funds through blended projects including PPPs».

[2] As reported by the European Court of Auditors, delays, cost increases and underutilization were due to insufficient analysis and inappropriate approaches. They found that the PPP choice was often without a sufficiently robust basis of analysis.

ity term and to account for unobserved differences between PPP and non-PPP firms. The ideal experiment would have a dataset in which PPP projects are randomly assigned, but in my case, the contracting authority choose whether to use PPP or not. I provide several robustness checks that account for selection due to contracting authority's unobservables. I compare PPP and non-PPP firms' performances in the context of a new network utility industry in the energy sector: the District Heating (DH).

A district heating is an integrated facility that generates thermal energy and distributes it among neighbor buildings through a network of pipes and heat exchanger substations. The DH service belongs to the category of network services, where the investments in the network and plant are high and largely not reusable in other sectors, therefore representing a sunk cost. Moreover, the European Commission considers DH technology as the preeminent substitute for gas boilers after their ban due to the REPowerEU plan.

This work utilizes a unique dataset covering the universe of Italian district heating facilities between 2007 and 2014. For each plant, I can observe accurate information on the physical quantities of output and inputs. Physical data are usually difficult to retrieve, although Tybout (2000) highlights how they are essential for identification in presence of omitted price bias. I use this information to construct a reliable proxy for capital quality in accordance with what the engineering literature indicates (see Dochev et al. (2018)), which is defined as the negative (-) ratio of the total length ($m$) of the pipeline to the total amount of heated volume ($m^3$) and it is measured as the length of pipeline required for every $100\,m^3$ of heated volume. DH embodies the perfect industry to observe the externality effect between the construction and the operation phases. In fact, the type of procurement affects the design of a pipeline, which plays the role of higher quality input in preserving the thermal capacity of a DH network.

For network utilities and, mainly, the DH sector, traditional procurement involves a severe moral hazard problem. When the capital quality is chosen by company A, but the cost of providing energy is carried by company B, company A does not internalize the reduced future marginal cost from lower heat losses. Then, company A finds that shirking on its delivered quality of infrastructure is optimal. It results in higher operating costs for company B. However, when a Consortium both constructs the pipeline and provides the service, it accounts in the construction stage for the reduced marginal cost of providing heating[3]. I show that a positive externality exists in this industry, and I measure the productivity effects of PPP contracts on district heating firms. My results show that capital quality has a positive and significant impact on the productivity of PPP firms. I find a non-significant marginal effect of my proxy for capital quality for non-PPP firms. There is, in turn, a substantial and highly significant marginal effect on output for PPP firms. In particular, increasing the measure of quality by one unit shifts up the expected change in the log of output by 0.161 for PPP firms. In level terms, this corresponds to an output increase of 17%. Overall, enforcing the same horizontal monitoring mechanism and setting the same level of capital quality as for PPPs, the average plant would be capable of producing 2922 $MWh$ of more energy and reduce $CO^2$ emissions of 1403 equivalent tons. The estimates of the production function parameters indicate the presence of decreasing returns to scale in the technology.

In the presence of a positive externality, not implementing PPP implies a lower level of welfare because firms could have produced more efficiently at a lower marginal cost. Alternatively, in the presence of a negative externality, implementing PPP would have been detrimental. Even if lower marginal costs might simply imply higher margins for the DHs and not lower prices, the impact on pollutant emissions is still relevant. I am the first to

[3] I report the case study of Zola Pedrosa district heating. On December 22, 2006, the project financing tender was awarded to the promoter, which formed the consortium consisting of SIME spa, SIME ENERGIA Srl, and CO.AR.CO. Srl, which later formed into a project company named ZOLA PREDOSA TELERISCALDAMENTO Srl. The authors of the research point out that the success of the whole operation is certainly due to the intense collaboration between the public and private parties. In particular, the chief engineer in charge of the project reports that "...The goal of our company is to have obtained a 25-year public concession, which allowed us to carry out an initiative relevant from an energy and environmental point of view. Our company is an ESCo, and we have other contracts with shorter duration and a different profitability; the longer duration of this concession allows us to have a long-term look and vary our presence in the market... At the technical level in the construction phase, we did not encounter any particular difficulties other than those typical of a project of this type, there was obviously a great deal of commitment and attention from both the personnel outside the company, who took care of the design and carried out the works and from the internal personnel, who exercised a function of control and management of the construction site...(pp. 157-158, see SIOP (2013)".

show that PPP works properly in an industry with characteristics in line with the assumptions stated in the literature. A public authority that knows in advance the gains/losses in terms of technical efficiency coming from PPP will have better guidance in the use of this procurement tool. This paper is related to Hoppe et al. (2013), where the authors conduct a laboratory experiment on PPP, and find that a PPP provides stronger incentives to make cost-reducing investments, which may increase or decrease service quality. Furthermore, this article provides more evidence on how public procurement can affect productivity. PPP is proved, similarly to fixed-price and cost-plus contracts, see Gagnepain and Ivaldi (2002), to be a driver of productivity and not only a solution to keep public bodies' investments high, despite reduced public budgets. The analysis results are robust to selection, measurement error, or misspecification of the functional form.

This article relates to two different strands of literature. First, I contribute to the literature on PPP with an empirical test for the predictions of these models. The first two articles that investigate the impact of public-private partnership are Hart (2003) and Bennett and Iossa (2006)[4]. In particular Hart (2003) provides a setting where a builder implements two non-contractible investments: a productive and an unproductive type. Both investments reduce operating costs, but only the productive investment increases the benefit of the builder. Under traditional procurement, the builder has not any increase in benefits or a reduction in cost from implementing the unproductive investment, so she finds optimal to exert too much of the productive investment, but only the minimum amount of the unproductive investment. Under PPP, the builder partly internalizes the externality of this unproductive investment by increasing it, but the level of the productive investment still remains too high. Bennett and Iossa (2006) introduce a model where investments are ex-ante non-contractible but ex-post verifiable. In this setting, they study in depth the desirability of bundling project phases and of assigning the ownership to the investor. Ownership implies the right to implement a quality-enhancing or cost-reducing investment. The problem of being kept from

[4]These articles built on Schmitz (2005), who sets a principal-agent model in which the principal decides how to organize a project that consists of two stages.

optimally investing in the first phase of the project is less severe under PPP when a positive externality between the building and the management phases exists. Furthermore, the authors show that public ownership imposes on government a commitment to share with the investor the surplus from the implemented investments. Martimort and Pouyet (2008) relax the hypothesis of non-contractible operational costs and non-contractible quality of the service. They obtain results similar to those of Bennett and Iossa (2006). In particular, they find that granting ownership imperfectly aligns the incentives of the agents; the important point is not who owns the asset, but whether the phases are bundled or not[5]. Agency costs are found to be lower under a PPP arrangement compared with traditional procurement in the presence of a positive externality between building and management. This article is also related to the contribution of Gagnepain and Ivaldi (2002) and Gagnepain et al. (2013), and it provides additional evidence on how procurement scheme can affect productivity.

Second, I contribute to the ongoing debate on productivity assessment and its dispersion. Bartelsman and Doms (2000) find many sectors where the most productive firm has more than twice the measured productivity of the least productive firm. Fox and Smeets (2011) observe that the mean ratio of the 90th quantile of productivity distribution to the 10th quantile is of 3.27 across eight Danish manufacturing and service industries. In this work, I identify a channel through which the procurement scheme affects total factor productivity (TFP): heterogeneity in the quality of capital input. In fact, large differences in productivity across plants in the same industry are related to unobserved heterogeneity in the quality of inputs. Balasubramanian and Sivadasan (2009), for instance, find that increases in capital resaleability are associated with a reduction in productivity dispersion. The empirical literature, in particular, has recently recognized the role of quality dispersion in inputs, see De Loecker et al. (2016), by investigating its impact on labor, see again Fox and Smeets

[5]Furthermore, Chen and Chiu (2010) introduce an "interim contractibility" framework and assume that the managing task becomes contractible subsequent to the building stage. Their results suggest that under private ownership, the technological externality and the task interdependence still play an important role in shaping the trade-offs between bundling and separation. In particular, convexity of the cost function, which allows for task complementarity, plays the interesting role of favoring the buyer's ownership and disfavoring the Consortium's ownership.

(2011) and Konings and Vanormelingen (2015), as well as on intermediate materials, see Atalay (2014) and Grieco et al. (2016).

The remainder of this article is structured as follows. In section §2, I present the district heating sector. In section §3, I describe in more detail the primary data sources. In section §4, I introduce the theoretical and empirical framework. The assumptions and the procedures to identify and to estimate the parameters of the model follow. Finally, I present the baseline results and a battery of robustness checks in section §5 and section §6.

## 2 Technical and Sectorial Background

A district heating (DH) is an integrated network system built under public concession to serve an urban neighborhood. The plants are intended to distribute thermal energy and co-generate electric energy. The electric energy produced is competitively sold to the national market, and the thermal energy is entirely redirected to an urban neighborhood through a system of pipes and distributive substations. The substations exchange the thermal energy between the main and the secondary pipelines of each building. Thermal energy transportation is carried out with a thermal vehicle (water or steam), running through the pipeline. A substation node can provide a certain amount of thermal energy to the urban neighborhood. If the thermal energy produced in co-generation is not sufficient to fully satisfy the demand, auxiliary boilers, which produce only thermal energy, fill the gap. I always observe an auxiliary boiler working, meaning that there is no free disposability of thermal energy. It implies that the electric energy production is constrained by the demand of thermal energy. Moreover, given that the ratio of electric and thermal energy produced is constant, DH is usually considered as a single product industry where electric energy is a residual product, see Brännlund and Kristräm (2001).

Substations are of central importance, and the majority of labor costs are related to their maintenance. A district heating substation is a component that connects the main network with a building's heating system. Substations, in particular, typically perform a number of tasks, including acting as a heat exchanger to separate the primary and secondary sides of the system, a control valve to regulate the flow through the heat exchanger, a differential pressure regulator to balance the network and increase the effectiveness of the control valve, a strainer to clear debris that could clog the heat exchanger or the control valve, a shut-off valve to stop the flow on the primary side in the event of an emergency, a heat meter to measure the energy consumption, a temperature controller to regulate the temperature on the secondary side by regulating the flow on the primary side, and a temperature sensor to detect the flow and return temperatures required for temperature control.

Transporting thermal energy to households implies heat losses over the traveled distance. Losses in the primary network are the third largest heat demand in a hot water network, after heat demand for the building and water heating. Many variables are involved when estimating pipe losses, such as the thermal conductivity of the soil and insulation, the supply and return temperatures, and the ambient temperature. When these variables are considered, it is easy to find sources of uncertainty. DH pipes are made of steel and buried in the ground. Moisture and water can cause the pipes to rust if the pipe jacket has a leak. This leads to holes in the pipe walls, resulting in leaks and heat loss. These losses should be kept as low as possible to achieve high efficiency of the network[6]. In this paper, heat losses are calculated as the difference between produced and consumed energy, so losses due to leakage are included.

The three most important parameters affecting losses in a DH network are: the pipe length, the supply and return temperatures, and the geographic distribution of heat demand. The pipe length is determined when the network is created. When planning new DH areas, the following steps are performed: a pilot study to determine the existing system, possibilities for reconstruction and incorporation of new parts into the existing network, heat demand for the new area; calculations of heat transfer capacity, power limits, heat losses; drawings for the contractor to execute the new piping. DH firms are concerned with a trade-off between

[6] According to Larsen et al. (2002) and Gabrielaitiene et al. (2007)

having more nodes or a shorter network of pipelines, and there is a high level of uncertainty about the final layout of the DH network, see Moras (2013). In theory, the design of the network could be ex-ante contractible. Still, in practice, due to the complexity of the design, the peculiar geology, the stratigraphy, and the abundance of archaeological sites of Italian municipalities, the final design strongly differs[7].

To evaluate the goodness of a DH network layout, the engineering literature suggests a linear thermal density measure[8]. The linear thermal density of a DH network is defined as the ratio between the length of the DH network (supply and discharge lines are counted as one unit) and the heat demand (approximated through the heated volume of the buildings), where higher density corresponds to a lower index. The more internalized this parameter is in the production stage, the more heat the DH can supply. This parameter depends on both the specific heat demand and changes of the network configuration over the years.

The type of contract handling the problem makes the difference. Under PPP where the future cost of management will fall upon the same firm, it is optimal to exert effort design and sustain the cost to make this parameter productive. Traditional builders exploits the minimum level of thermal density required in the contract, or required by circumstances beyond the contract, but PPP firms have incentives to do better.

The investment in network and plants is high and mostly not reusable in other sectors and, therefore, a sunk cost. The only possible economies of scale are connected to the distribution of fixed costs over many users. However, the network's dimension cannot be overextended to avoid thermal loss increases. DH firms stipulate contracts of service with the customers of the network, and each household is usually served by only one DH network.

[7]The biggest problem as confirmed by the contracting authority and the chief engineer in charge of the district heating of the municipality of Zola Pedrosa is that "... regarding the construction of the district heating, the most important risk hazard concerns the underground utilities, unfortunately, most of the municipalities in Italy do not have cartography regarding the underground utilities. So to get this documentation, you have to go to all the authorities and very frequently when they have the mapping, it is not reliable because during the excavation works, there is a discrepancy (p. 160, see SIOP (2013)" .

[8]Other thermal density measures exist, but linear thermal density has the advantage over area-based thermal density measures, that irrelevant urban areas are not included. Since linear thermal density directly uses grid length, it is a better measure, see Dochev et al. (2018).

The size of the investment makes the construction of two networks in the same geographical area unlikely and the most frequent choice for users will not be between DH networks, but between different technologies of heat production. Once the choice of connection to a network has been made, if the user wants to switch to other technologies, he must incur switching costs, however minimal.

In the context of DH in Italy, systems were fully originally municipally-owned and operated. The top 3 largest and oldest DH (Brescia, Milan and Turin) were owned and operated by their respective city governments, which also handled other utility services such as electricity and water. Eventually, private money came to fund further improvements of the grid, but actually not taking over the property (public property share were kept at 51%). The largest DH player is A2A which was formed through the merger between the AEM (owned by the city of Milan) and ASM (owned by the city of Brescia) in 2007. Newer (and smaller) DH systems in other cities are partially private funded, both under public concession or PPP. In the last decade, PPPs have accounted for 13% of the contracts in the DH sector and 35% of the value of the entire market, see SIOP (2013). The same study evaluates DH as a growing sector. .

DH sector has some structural characteristics typical of "network industries" (high sunk costs, switching costs) and the presence of economies of density and scale makes a single distribution network more convenient. Consequently, the DH is usually provided by a local monopolist. A recent study by the Italian Competition Authority (ICA), see Esposito (2017), reports that Italian DH firms rarely earn high extra-profits. The legislative indications about distribution tariffs remain rather generic and, typically, refer to the regulated price of methane gas for domestic supplies. Since households can install a private heating system, DH firms anchor the price of the service to the cost of running an autonomous boiler as heating source.

# 3 Data

I exploit an original dataset describing the DH industry between 2007 and 2014. These data are released every year by the AIRU, the Italian association of DHs, as a collection of detailed plant files, and cover a total of 148 plants (almost the entire population). For each plant, I have accurate information about the production process in terms of physical quantities. A sample of these plant files is available in fig.2. Most plants, as fig. 1 shows, are located in the north of Italy, where temperature conditions and heating periods justify economically that a plant operates more than 2 months per year. In fig. 1, the total amount of heated volume (my proxy for the heat demand) is mapped in darker shades of gray revealing Northwest Italy as the area where DH is most established and widespread.

For each plant, I observe accurate information about output in terms of thermal energy measured in megawatt-hour, $MWh$, produced and distributed. Distributed thermal energy ($ED$) is the main output variable.

I also observe the amount of heat energy lost ($ET$) measured in $MWh$, which is the intermediate material and the proxy variable in the structural model. By observing both the whole thermal energy implied in the distribution process and the heat losses of the pipeline in megawatts per hour ($MWh$), I can divide the thermal energy delivered to neighbor buildings from the thermal energy directly related to the distribution process. Using thermal energy greatly simplifies the analysis since a single homogeneous input is considered in place of several possible propellants implied in the production process of thermal energy.

Furthermore, the dataset provides useful information about the inputs. Two proxies of capital are available: the count of the heat exchanger substations, which work as nodes of distribution of the thermal energy to a neighborhood of buildings; and the length of the pipeline, measured in $m$. Heat exchanger substations are a proxy for the capital input and can differ in terms of thermal capacity. By assuming a constant temperature of operation, firm size dummies control for this kind of heterogeneity. Other aspects related to capital quality may influence the distribution process, so I use the length of the pipeline as a capital quality proxy.

A set of dummies which indicate some key differences in DH technologies are introduced. First, I control for the thermal vehicle used (steam or heated water), which can make a difference to the rate of dispersion. Second, the majority of plants co-generate thermal and electric energy. Producing thermal energy without electricity could have a severe impact on the dimension of a plant.

There are important heat demand shifters, which influence production decisions of DH firms. First, geographical dummies are introduced to control for different average temperatures across different areas. I construct three main geographical zones exploiting an European thermal energy index, referred to as "*heating degree-days*" (abbreviated as GG from the Italian version of the index), and use it to assess the average use of thermal energy of a city. This measure was introduced by European standard EN ISO 15927-6 and is defined as:

$$GG = \sum_{1}^{d} (20 - T_e)$$

where $d$ is the maximum number of days of the conventional heating period and ranges between 90 and 365; 20 degrees Celsius is the conventional ambient temperature in Italy; and $T_e$ is the daily average outer temperature. A low value of $GG$ indicates a short period of heating and daily temperatures near to the prescribed temperature for the environment. The three zones are constructed based on climatic bands defined by the European standard: Zone 1 is comprised between 1400-2100 GG, Zone 2 between 2100-3000 GG,and Zone 3 above 3000 GG. Second, I introduce a continuous variable which measures the amount of thermal energy extracted by the average building. I exploit the percentage of Celsius degrees difference of ingoing and outgoing temperature of the thermal vehicle. This difference is commonly used by the engineering technical literature and the index is a standardized measure of average thermal energy dispersion that catches shifts in heating demand due to thermal isolation of houses.

I employ heated volume of buildings measured in $m^3$ to construct firm size dummies. First, I add these dummies to fix the heated volume and to interpret the change in capital quality as a change in pipeline length only. Second, these dummies also control for big shifts in the thermal capacity of DH firms.

In order to identify the plants constructed under PPP, I exploit a research published by SIOP and the Chamber of Commerce, see SIOP (2013). I account for a total of 25 projects between 2002 and 2013 realized using PPP.

Finally, I integrate data on the number of workers by directly collecting them from the balance sheet of each company. These data refer to full-time blue-collar employees.

In table 1, I report descriptive statistics of the entirety of firms along with those for each group, PPP or not. At first glance, the average PPP firm looks different than the average non-PPP firm, smaller in terms of output and inputs capacity. It is due to some big plants, which bias means and standard deviation. Looking at medians and interquartile range, PPP and non-PPP are closer. It is interesting to notice that with a similar usage of inputs (pipeline length, substations, and heat losses), PPP can serve a higher heat demand (740.48 against 504.70 $\times 10^3\, m^3$) and produce less $CO^2$ (3345 against 5699 tons). The average heated volume for Italian DH firms is around $2377 \times 10^3\, m^3$, and the median is around $508 \times 10^3\, m^3$. The average and median temperature extracted are 30.45 and 25 degrees Celsius. Only 24% of non-PPP firms do not produce electric energy, whereas almost the entire PPP sub-sample, 95%, produces in a co-generation regime. 44% of the entire sample use heated water as a thermal vehicle over steam. PPP firms are mostly located in Zone 2 (85%) and show a smaller value (higher quality) of the capital quality proxy.

I investigate for a mechanism through which PPP influences the quality of the infrastructure. In order to understand the channel, I exploit the network nature of a DH's pipeline. Capital quality, $a$, is defined as the negative (-) ratio of the total length of the pipeline to the total amount of heated volume

$$a = -\frac{pipeline's\, length}{heated\, volume}$$

and measured as the length of pipeline required for every $100\, m^3$ of heated volume. This ratio captures the impact on output of the thermal density of the network. PPP firms have higher median thermal density, and increasing values have a positive impact on output due to reduced heat losses. PPP firms show a higher median quality of capital index than non-PPP firms ($-0.15$ against $-0.20\ m/100\, m^3$). The theoretical literature suggests that under traditional procurement, a builder has no incentive to improve the minimum level of capital quality. Under PPP, instead, since the operator is involved in the building's design phase, she can state the optimal level of capital quality she needs.

# 4 Model

## Theoretical framework

Under traditional procurement, a contracting authority could offer to the builder (B) a contract with the payment scheme $\tau_B + \gamma_B C_B$ with $\{(\tau_B, \gamma_B)\} \in \mathbb{R} \times [0, 1]$, where $\tau_B$ is a transfer from the authority and $\gamma_B$ the percentage of cost ($C_B$) shared with the firm. The case $\gamma_B = 1$ corresponds to a cost-plus contract where the contractor is fully reimbursed for its own costs, whereas $\gamma_B = 0$ stands for a fixed-price contract, where the contractor receives a fixed payment. Fixed-price contracts are of common use for DH construction, then only $\tau_B$ is contractible.

The same public authority could offer to the operator (O) a range of contract with the payment scheme $\tau_O + \gamma_O R_O$ with $\{(\tau_O, \gamma_O)\} \in \mathbb{R} \times [0, 1]$, where $\tau_O$ is a transfer from the authority and $\gamma_O$ the percentage of revenues shared with the firm. A payment mechanism based solely on user charges corresponds to $\tau_O = 0$ and $\gamma_O = 1$, so that the contractor keeps all the revenues. On the other hand, a payment mechanism based on availability corresponds to $\tau_O > 0$ and $\gamma_O = 0$, so that the contractor's reward is fixed. DH firms collect the entirety of revenues from customers.

Every time a new DH network is created or expanded a contracting authority faces the problem of implementing a minimum level $\underline{a} \in \mathbb{R}_+$ of facility quality, below which the plant does not work, and eventually a quality investment $a^i \in \mathbb{R}_{++}$, which will influence the operational cost of the operator and increase the overall quality of capital, $a$[9].

## Moral hazard

Suppose the following well-behaved firm's cost function, which is differentiable on every point of the domain:

$$C(ED,\, a,\, e;)$$

with $\frac{\partial C(.)}{\partial a} \leq 0, \frac{\partial C(.)}{\partial e} \leq 0$ and $\frac{\partial C(.)}{\partial ED} \geq 0$. The total cost is a non-decreasing function of the distributed thermal energy, $ED$. The total cost is a non-increasing function of the effort, $e$, and the capital quality, $a$; the amount of each input required to produce the same level of output is reduced or unaffected by rising effort and capital quality. The effort, $e$, encompasses all these factors which the IO literature has recognized as effectively able to reduce firm unit cost, see Syverson (2011) for a survey. Referring to the procurement literature, Gagnepain and Ivaldi (2002)'s reduction of inefficiency in the public transportation sector due to the enforcement of procurement contracts on suppliers, represents a good example of the role played by moral hazard.

Under traditional procurement, the builder knows nothing about the cost structure of the operator, so implementing a particular quality investment level $a$ affects her own cost negatively. This cost of implementing $a$ is an unknown function $v(a)$ with $\frac{\partial v(.)}{\partial a} > 0$. Then,

[9] The overall quality of capital, $a$, is actually time variant because $a_t = a_0 + (a_1 - a_0) + ... = \underline{a_0} + (\underline{a_1} - \underline{a_0} + a_1^i) + ...$, and it is cumulative. Although, I observe that DH firm's investment happens every 2-5 years, which makes its dynamic less relevant.

the builder's optimization problem, who receives a first price payment scheme, $\tau_B > 0$ and $\gamma_B = 0$, would be:

$$\underset{a \geq \underline{a}}{max}\, \tau_B - v(a)$$

where the builder decides to optimally implement the smallest capital quality level, $\underline{a}$, in order to make the plant operative[10]. At the production stage, the operator can exert an effort $e$ in order to reduce the "input" inefficiency of her own cost. The cost of implementing effort $e$ is the unknown function $z(e)$ with $\frac{\partial z(.)}{\partial e} \geq 0$. The optimization problem of the operator who receives a payment schemes $[\tau_O, \gamma_O]$ and takes $a = \underline{a}$, is:

$$\underline{e} = arg\, \underset{e \geq 0}{max}\; \tau_O + \gamma_O R_O - C(ED,\, \underline{a},\, e;) - z(e) \tag{1}$$

In a PPP, a contracting authority offers to the builder and the DH, jointly in a consortium (C), a unique contract. The optimization problem is:

$$\left(a^{PPP},\, e^{PPP}\right) = arg\, \underset{a \geq \underline{a},\, e \geq 0}{max}\; \tau_C + \gamma_C R_C - C(ED,\, a,\, e;) - z(e) - v(a) \tag{2}$$

that delivers the following capital quality level and effort investments:

$$a^{PPP} := \underline{a} + a^i_{PPP}$$

$$e^i_{PPP} := e^{PPP} - \underline{e}$$

[10] A fixed-price contract will not determine an investment in quality, $a$, if this investment is not implemented as reducing the builder's cost effort. A different payment scheme linked to the quality investment provided by the builder obviously determines some quality investment implemented also under classical procurement.

under traditional procurement, the level of implemented capital quality cannot exceed the level of capital quality set by the builder, which means that the total level of capital investment $a^i_{PPP}$ is equal to zero. The level of capital quality has an increasing marginal productivity when the gain from investing $\frac{\partial C(.)}{\partial a}$ is not fully neutralized by the cost loss term, $\frac{\partial v(.)}{\partial a}$. When the implementation phase is unsuccessful, meaning that the operating firm has not been able to make the quality of capital productive, the effect on productivity may be zero or even negative. In appendix A, I propose an explicit solution for technical efficiency under the assumption of a Cobb-Douglas unit cost function and exponential costs of implementing $a$ and $e$[11]. In this case, the externality effect will result in a productivity effect through duality.

The effect on the total level of effort is less clear, since it is related to the convexity of the cost function through the cross derivative $\frac{\partial C(.)}{\partial a \partial e}$. When $\frac{\partial C(.)}{\partial a \partial e} > 0$, we should observe substitution between the total level of effort and the capital quality. I do not have any hint about the true direction of the cross derivative, but I can rely on the control function approach to control for such effects in my empirical model.

## Empirical model

I assume the following DH firm's single-output structural valued-added Cobb-Douglas production function:

$$ED = \Omega\,(a,\, e;\, PPP) \cdot K^{\alpha_k} \cdot L^{\alpha_l} \tag{3}$$

where $ED$, $K$, $L$ are respectively output, capital and labor, and $\Omega\,(.) = \exp\,[\omega\,(.)]$ is the unobserved term for productivity. In particular, $ED$ is the amount (megawatt per hour, MWh) of thermal energy delivered. First introduced by Gandhi et al. (2020) and employed by Ackerberg et al. (2015), this specification of the production function assumes proportionality

[11] In Appendix A, I parameterize the domain of the tfp function through two exogenous parameters $\delta$, $\kappa \in [-\infty, +\infty]$. These parameters capture the externality effect of capital quality and labor effort.

between intermediate material, $ET$, and output, $ED$[12][13]. In particular, $ET$ is the thermal energy implied to cover heat losses and plays a main role in the empirical model since it is the proxy variable for productivity estimation.

Under traditional procurement (TP), on the one hand, firms implement the lower capital quality level $\underline{a}$. On the other hand, PPP induces firms to make a quality investment $a^i_{PPP}$. The following expression defines the total capital quality implemented by a DH firm (considering both PPP and TP cases) :

$$a = a^{PPP} \cdot PPP + \underline{a} \cdot (1 - PPP) = \underline{a} + a^i_{PPP} \cdot PPP$$

where $PPP$ is a binary variable to identify PPP plants. Based on the curvature of the cost function, PPP firms adjust the operating effort, $e$, given the quality design investment, $a$. Similarly to quality, I can define the total effort as:

$$e = e^{PPP} \cdot PPP + \underline{e} \cdot (1 - PPP) = \underline{e} + e^i_{PPP} \cdot PPP$$

I assume separability of $\omega(a, \text{e}; PPP) = \omega^{TP} + (\omega^{PPP} - \omega^{TP}) \cdot PPP$, where $\omega^{TP}$and $\omega^{PPP}$ are at least $C^1$ functions. Taking a first-order Taylor expansion in zero and collecting PPP and non-PPP firms, I obtain:

[12] The structural value-added production function is directly derived from the following DH firm's single-output gross output Leontief production function:

$$ED = \min\{\Omega \cdot K^{\alpha_k} \cdot L^{\alpha_l},\, \alpha_{et} ET\}$$

The intermediate materials, $ET$, are considered proportional to the output. After controlling for climatic and environmental factors, heat losses grow according to the amount of output, and their final value is related to the thermal density parameter and the ability to maintain substations and pipes. Productivity is also related to this ability.

[13] A Leontief production function avoids the issue with the estimation of the intermediate material input elasticity. As highlighted by Gandhi et al. (2020), the Leontief form could be insufficient to guarantee the identification of the elasticities. To understand, suppose $K_{it}$ and $L_{it}$ are chosen before $ET_{it}$ and the price of $ET_{it}$ suddenly changes such that revenues do not cover the cost of the intermediate material required to produce that output. In this case, DH firms would not generally choose $ET_{it}$ to satisfy ED=$\alpha_{et}$ET= $\Omega \cdot K^{\alpha_c} \cdot L^{\alpha_l}$, and thus the data could contain points where production is equal to zero. This does not appear as a huge issue, however, since DH firms will either satisfy ED=$\alpha_{et}$ET= $\Omega \cdot K^{\alpha_c} \cdot L^{\alpha_l}$ or produce zero output, and if they produce zero, they will presumably not be in the dataset of those operating and thus it is not a problem for estimation, Ackerberg et al. (2015).

$$\omega(a,\,\text{e};\,PPP) \backsimeq \underbrace{\left[\frac{\partial \omega^{TP}}{\partial a}\right]}_{\beta_a} a + \underbrace{\left[\frac{\partial \omega^{PPP}}{\partial a} - \frac{\partial \omega^{TP}}{\partial a}\right]}_{\beta_{int}} a \cdot PPP +$$

$$+ \underbrace{\left[\omega^{PPP} - \omega^{TP}\right]}_{\beta_{PPP}} PPP \tag{4}$$

where the constant components are omitted for the sake of simplicity[14]. By plugging $\omega(a,\,\text{e};\,PPP)$ into the linearized Cobb-Douglas production function, in equation (3), the reduced-form model for a DH firm $i$ in time $t$ can be written as:

$$ed_{it} = \alpha_k k_{it} + \alpha_l l_{it} + \beta_a a_{it} + \beta_{int}\left(a_{it} * PPP_i\right) + \beta_{PPP} PPP_i + \omega_{it} + \epsilon_{it} \tag{5}$$

where small cases stay for logs of output and input variables. The unobserved terms relative to $e_{it}$ are absorbed inside $\omega_{it}$, the unobserved productivity term along with the other unobserved factors, which influence productivity. The idiosyncratic error $\epsilon_{it}$ accounts for measurement error. The coefficient $\beta_{PPP}$ should be interpreted as the PPP effect on output, which captures the mixed effect of trading-off quality investment and operational effort, as well as institutional unobserved factors relative to PPP. The interaction term $\beta_{int}$ is the incremental effect of a unit increase of capital quality when a firm is built and operated under PPP. This should be interpreted as the externality effect on productivity. On the other hand, the coefficient $\beta_a$ measures the overall marginal effect of the capital quality $a_{it}$.

The identification of $\beta_{int}$ and its interpretation as the effect of the technological externality is based on a simple feature of the linear model in equation (6):

$$ed_{it} = \alpha_k k_{it} + \alpha_l l_{it} + \beta_a a_{it} + \beta_{int}\left(a_{it} * PPP_i\right) + \beta_{PPP} PPP_i + \sum_{q=1}^{4} \beta_s s_{it}^{q} + \omega_{it} + \epsilon_{it} \tag{6}$$

[14] The full expansion is available in Appendix C

by introducing size dummies, $s_{it}^q$, for the quartiles of the heated volume, $m^3$, I avoid variation in the quality index due to variation of the heated volume. In this way, changes in this index are only due to changes in the pipeline length. In addition, the model can accounts for others control variables controlling for technological and supply shifters. For the sake of simplicity, I collect all the terms, apart from the marginal elasticities of the inputs, and the other control variables in vector $\mathbf{x_{it}}$, the model collapses to:

$$ed_{it} = \alpha_k k_{it} + \alpha_l l_{it} + \mathbf{x_{it}}\beta + \omega_{it} + \epsilon_{it}$$

The vector $\mathbf{x_{it}} = [a_{it},\ PPP_i,\ a_{it} * PPP_i,\ \mathbf{d}_i,\ Cog_i,\ Tech_i,\ dTemp_{it},\ \mathbf{s_{it}},\ 2014_t]$ contains all the relevant control variables for the DH's distribution process. The $\mathbf{d}_i$ vector includes all the geographical dummies. The $Cog_i$ dummy controls for plants in co-generation regime. A $Tech$ dummy, equal to 1 for heated water, is included to control for technological differences in the physical state of the thermal vehicle (heat water, steam). The $dTemp_{it}$ variable is the continuous index which measures the average thermal dispersion of buildings. The $\mathbf{s}_i$ vector includes firms size dummies $s_{it}^q$ with $q = 1, \ldots, 4$. The $2014_t$ is a dummy I added to control for the particularly hot winter of 2014.

Estimates of equation (5) by OLS will incur the well-known endogeneity problem associated with estimating production functions: the presence of $\omega_{it}$ ($e_{it}$) being possibly correlated with labor intermediate demand [15]. Klette and Griliches (1996) refer to this endogeneity as *simultaneity*, since output and inputs result as the solution of a simultaneous equations system. Methods of solving the simultaneity problem include finding instruments for inputs or assuming a time invariant productivity and using a fixed-effects estimator, see Mundalk

[15] More generally, the issues of the estimation of a log-linearized version of equation (3) can be twofold. The model is expressed in terms of physical quantities of inputs and outputs. In place of physical output and inputs, scholars often use proxies. Sales deflated by an industry-wide price index are commonly used in place of the output, and balance sheet data substitute for inputs. Such substitutions have no consequences under perfect competition, since all firms observe the same prices. With imperfectly competitive markets, however, the estimated firm-level productivity is misstated due to the effect of unobserved demand-shifters, affecting through prices the proxies for output and inputs. Since the problem originates from omitted prices, it is usually referred as omitted price bias.

(1961). Both methods seem to have failed. Input prices are usually weak instruments for quantity. Conversely, assuming time invariant productivity would not explain how period by period changes in productivity would be responsible for changes of input choices. Olley and Pakes (1996), Levinsohn and Petrin (2003), and Ackerberg et al. (2015) have proposed a structural approach, which exploits observed plant decisions as proxies for unobserved productivity shocks. The intuition relies on the existence of a proxy variable for productivity, which reacts to variations in TFP. If this function is proved to be invertible, the inverse function can be estimated and plugged into the production function to control for endogeneity [16]. In this industry, productivity differences may also owe to unobserved differences in quality of inputs as well as to previously unobserved differences in plant characteristics due to the form of procurement used. In order to account for this endogeneity, I adapt the Ackerberg et al. (2015) to the DH industry, and I introduce a new state variable for capital quality under the two different procurement schemes.

First, I specify the inputs timing decision and the DH firm's static optimization problem to separate the dynamic state variables from the static free variables. Second, I explain how the input coefficients are identified exploiting the information set at time $t$. Third, I discuss possible concerns relative to the selection of the sample.

[16] Olley and Pakes (1996) isolate the proxy variable directly from the investment dynamic optimization problem of a firm, by inverting the amount of investment. From the dynamic problem the terminology is also inherited, with the variables that constitute the minimum set of information required to retrieve the policy function (the stock of capital, the age of a firm, etc.) referred to as dynamic state variables. Inputs (labor, materials, etc.), which are modifiable in a later period after productivity shocks occur, are referred to as static free variables. Investment as a proxy for TFP has an enormous problem in terms of data availability. Since in many cases investment assumes a zero value, it becomes not invertible on these points. Consequently, many observations must be dropped and the remaining sample needs to be representative. Levinsohn and Petrin (2003) propose a different approach by slightly changing the timing of a firm's decision. If intermediate materials (energy, fuels, etc.) are chosen between the occurrence of the productivity shock and the decision regarding the optimal level of free variables, they respond monotonically to productivity and act as a suitable proxy variable. The static variable intermediate materials do not suffer from the zero value problem and guarantee greater data availability. Ackerberg et al. (2015) point out that the choice of free variables (labor, etc.) is a function of previous choices in terms of dynamic state variables. Consequently, any attempt to estimate separately free variables coefficients could suffer from a serious problem of collinearity. They propose abandoning estimating the elements of the coefficient vector $\alpha$ simultaneously.

## Identification

A problem for identification is the endogeneity due to simultaneous output and inputs. In this case, identification is obtained through a structural model exploiting the timing assumption behind a DH firm's dynamic optimization of profits.

### Timing assumptions

A DH plant chooses the amount of the intermediate materials based on its stock of capital, $K_{it}$, labor, $L_{it}$, and a vector of observable characteristics of the plant, $\mathbf{x}_{it}$. This vector of observable characteristics contains information about the technology, demand, and the procurement shifters, which affect the optimal level of capital quality of the network, $a_{it}$. The decisions at period $t$ unfold as follows:

1. Output choice. At the beginning of the period, a manager of a DH plant knows the current level of capital, $K_{it}$. The manager also observes $\Omega_{it}^{BEFORE}$, her belief on productivity this period given the information set at the beginning of the period, which is also a function of the effort, $e$, the quality investment, $a$, and a vector of other observable control variables.

   $$\Omega_{it}^{BEFORE} \equiv E[\Omega_{it}^{AFTER}|I_{it}] = E[\Omega_{it}^{AFTER}|K_{it},\, L_{it},\, \mathbf{x}_{it},\, \Omega_{it-1}^{AFTER}]$$

   Relying on this information set., $I_{it} = (K_{it},\, L_{it},\, \mathbf{x}_{it},\, \Omega_{it-1}^{AFTER})$, the manager of a DH plant decides the targeted level of output.

2. In an intermediate period between output choice and production, the manager decides the amount of needed labor input, $L_{it}$. Note that the decision about the level of labor input is not "perfectly variable" at the time production takes place; the timing of decisions regarding the inputs implies that labor is a less variable input since labor is

chosen one subperiod before productivity shocks occur.

3. Production occurs. Based on the chosen targets, the plant carries out its distribution activity and observes realized outcomes for output and losses of the network. The DH manager of a DH firm also updates his knowledge about productivity, $\Omega_{it}^{AFTER}$.

4. Intermediate inputs choices. During production, free variables are adjusted to reflect what has been learned about productivity, the information set $I_{it} = (K_{it},\, L_{it}, \mathbf{x}_{it},\, \Omega_{it}^{AFTER})$ is updated. With this new piece of information, the manager decides on intermediate inputs, $ET_{it}$;

5. New period decision starts

As expectations on productivity at $t$ are formed, the manager chooses whether the plant has to remain active in the market in period $t+1$, and if so a new cycle starts[17].

### A static optimization problem

I follow the examples of Levinsohn and Petrin (2003) and Ackerberg et al. (2015) in solving the static profit maximization problem only, which is sufficient in order to identify the production function parameters. At the beginning of the period, the manager chooses the inputs to solve the following static profit maximization problem[18]:

$$\pi(K_{it},\, ET_{it},\, L_{it},\, \Omega_{it},\, \mathbf{x_{it}}) = \max_{ET_{it},\, L_{it},} E[P_{ED} \cdot ED_{it} - P_K K_{it} - P_{ET} ET_{it} - P_L L_{it} | \mathbf{x_{it}}]$$

[17] In the sample there is just a single plant shutting off, so I do not need correction for this kind of attrition.

[18] $P_{ET}$ is the price of the extra energy produced to cover losses in distribution. The price is equal to the price of fuel or combination of prices (if many fuels are used).

$$s.t.\ ED_{it} = F(K_{it},\, ET_{it},\, L_{it},\, \Omega_{it}^{BEFORE}|\mathbf{x_{it}})$$

Lastly, the following lemma establishes that the intermediate materials demand, $ET_{it}$, is strictly increasing in productivity, which is a sufficient condition for invertibility, and allows me to use intermediate materials demand as a proxy for productivity in our estimation strategy. The following is proved in appendix B:

**Lemma 1.** The plant's intermediate material demand, $et_{it}$, is strictly increasing in $\Omega_{it}^{AFTER}$ if the following condition on the production function holds:

$$\frac{\partial F}{\partial ET \partial L} \frac{\partial F}{\partial ET \partial \Omega^A} - \frac{\partial F}{\partial ET \partial \Omega^A} \frac{\partial F}{\partial L^2} + \frac{1}{\eta F} \left( \frac{\partial F}{\partial ET} \frac{\partial F}{\partial \Omega^A} \frac{\partial F}{\partial L^2} - \frac{\partial F}{\partial ET \partial \Omega^A} \frac{\partial^2 F}{\partial L} - \frac{\partial F}{\partial L \partial ET} \frac{\partial F}{\partial L} \frac{\partial F}{\partial \Omega^A} - \frac{\partial F}{\partial L} \frac{\partial F}{\partial ET} \frac{\partial F}{\partial L \partial \Omega^A} \right) > 0$$

the first part of the expression outside the brackets is the same condition that Levinsohn and Petrin (2003) identifies under the case of perfect competition. The second part inside the brackets captures the adjustment on the intermediate material demand that a firm sustains to exploit its market power. Fortunately, this condition holds in many production function as verified by DeSouza (2006) for firm's residual demand.

### Selection concerns: Public bodies and Firms

Contracting authority decision about PPP adoption is exogenous relative to firms. Firms are exposed to the tender, but they cannot decide the form of procurement. However, the choice of procurement by public bodies can be the result of their selection. In Table 4, a PPP dummy is regressed on the public body's characteristics, political composition of ruling parties, several measures of corruption and area and time fixed effects. Table 4 presents both linear probability estimates and probit marginal effects (at the median). Among the contracting authority's characteristics, the ratio between the actual and expected tax revenues, a measure of fiscal efficiency often used in political economy literature as a proxy for administrative quality, see Gagliarducci and Nannicini (2013), is found to be positively correlated with the probability of adopting a PPP contract. This proxy is meaningful because procurement practitioners have recognized the complexity of these instruments, and a more capable administration can handle PPP more appropriately. In section §6, I present a further model, where a third step accounts for public bodies' selection due to the administrative quality. The model results do not differ a lot from the baseline model.

In table 4, I also test for several proxies of corruption; in columns 1-2 the proxy is the stock of corruption measured by the Golden-Picci index proposed by Golden and Picci (2005), in columns 3-4 it is the number of public workers denounced for corruption, and in columns 5-6 it is the number of procurement experts denounced for corruption. None of these proxies has a significant effect on the probability of choosing PPP.

Any seller's expertise about peculiar procurement procedures may represent an issue because specialized sellers could only apply. In the presence of this kind of selection, the effect of the PPP on technical efficiency could be due to the selection of a particular subsample of firms. In order to address these possible concerns, I exploit tender awards data to assess the status of the DH market in terms of relative market shares of DH firms. The insight is that in the presence of selection, the market structure of PPPs should be different from non-PPPs. I find that seven firms represent 56.51 % of the entire PPP market (table 2). The same seven firms (Cofely and Siram are connected in terms of ownership) account for 47.53 % of the non-PPP market (table 3). After comparing PPP with non-PPP projects, firms seem to retain their relative market share, and I cannot find any evidence of firms specialized in PPP projects only.

PPPs and non-PPPs are not directly comparable in terms of contract objects, since PPPs bundle different tasks[19]. Such heterogeneity could induce some restrictions on competition among DH firms, which translates in selection: maybe small firms cannot compete in very

[19] A useful discussion is in Saussier et al. (2009).

big tenders. The poor/good outcome of PPP plants could again be the result of a selection of big/small or low/high quality firms. In order to check this out, I analyze a sample of 33 tenders in the period 2007-2012 (earlier data are not available). In table 5, it is possible to compare the average number of bids made in PPP tenders with the average number of bids for building, operating and maintenance tenders. In this case, the number of bids proxies the level of competition in the tender. The average number of bids for a PPP tender is 4.08 with a standard deviation of 5.99 (right column in table 5). The mean of the average number of bids for building, operating and maintenance of a non-PPP tender is 5.39 with a standard deviation of 2.85 (weighted mean of the left column in table 3). A non-directional t-test (t-statics equal to 0.77 with 31 degree of freedom) confirms that the difference between the means of two independent samples is not statistically different from zero. Additionally, in section §6, I present a further model where the firm's entry decision is taken into account, but I do not find evidence of this bias.

## Estimation

After production occurs, the manager of a plant updates her beliefs about productivity and she will observe the new variable:

$$\omega_{it}^{A} = \omega_{it}^{B} + \epsilon_{it}^{\omega} \tag{7}$$

where $\omega_{it}^{A} = log(\Omega_{it}^{AFTER})$ and $\omega_{it}^{B} = log(\Omega_{it}^{BEFORE})$. Since the intermediate material demand is a function of $\omega_{it}^{A}$, the model needs to be restated. Plugging equation (7) into model equation (5), it can be rewritten as:

$$ed_{it} = \alpha_k k_{it} + \alpha_l l_{it} + \mathbf{x_{it}}\beta + \omega_{it}^{A} - \epsilon_{it}^{\omega} + \epsilon_{it}$$

The vector $\mathbf{x_{it}} = [a_{it}, PPP_i, a_{it} * PPP_i, \mathbf{d}_i, Cog_i, Tech_i, dTemp_{it}, \mathbf{s_{it}}, 2014_t]$ contains all the relevant control variables for the DH's distribution process. $PPP_i$ identifies PPP plants. The $\mathbf{d}_i$ vector includes all the geographical dummies. The $Cog_i$ dummy controls for plants in co-generation regime. A $Tech$ dummy, equal to 1 for heated water, is included to control for technological differences in the physical state of the thermal vehicle (heat water, steam). The $dTemp_{it}$ variable is the continuous index which measures the average thermal dispersion of buildings. The $\mathbf{s}_i$ vector includes firm size dummies $s_{it}^q$ with $q = 1, \ldots, 4$. The $2014_t$ dummy controls for the particularly hot winter 2014. I assume that $(\epsilon_{it},\, \epsilon_{it}^{\omega})$ is mean zero and uncorrelated with the information available, although the components of this vector may be correlated with each other. Because the manager will not learn about $(\epsilon_{it},\, \epsilon_{it}^{\omega})$ until the plant operates, she has to optimize the output choice under uncertainty.

The vector $(\epsilon_{it},\, \epsilon_{it}^{\omega})$ does not raise any endogeneity problem. This vector is revealed to the DH manager after she makes her input choices and it is uncorrelated with the information set at the time output choices are made. The expectation $\omega_{it}^B$, forces me to control for $\omega_{it}^A$ since $l_{it}(\omega_{it}^B)$ is also a function of $\omega_{it}^A$. From Lemma 1, the DH firm's expectation about its productivity can be recovered by inverting the series of intermediate materials choices such that

$$\omega_{it}^A = et_{it}^{-1}(et_{it},\, k_{it},\, l_{it},\, \mathbf{x_{it}}) \tag{8}$$

I follow Ackerberg et al. (2015) in substituting equation (8) into the production function in order to obtain the first stage equation:

$$ed_{it} = \alpha_k \cdot k_{it} + \alpha_l \cdot l_{it} + et_{it}^{-1}(k_{it}\, et_{it}\, l_{it}\, \mathbf{x_{it}}) - \epsilon_{it}^{\omega} + \epsilon_{it}$$

$$= \Phi(k_{it}\, et_{it}\, l_{it}\, \mathbf{x_{it}}) + \varepsilon_{it} \tag{9}$$

where $\Phi$ is a polynomial in $(k_{it},\, et_{it},\, l_{it},\, \mathbf{x_{it}})$. First stage does not identify coefficients due to the collinearity issue. First stage is meant to get rid of the error component, $\varepsilon_{it} = \epsilon_{it}^{\omega} + \epsilon_{it}$, and to obtain the sample counterpart $\hat{\Phi}$ from a non-parametric estimate of equation (9).

Under the LP assumptions and at the true value of the coefficient vector $(\alpha_j^*,\, \beta_x^*)$ with $j = k,\, l$ and $x = a,\, ...,\, d^1, .., d^n,\, ...2014_t$, $\hat{\Phi}$ could be used to recover a reliable proxy of the productivity $\omega_{it}^A$. The sample counterpart of $\omega_{it}^A$, $\widehat{\omega}_{it}$, is then obtained as:

$$\hat{\omega}_{it} = \hat{\Phi}_{it} - \alpha_k^* \cdot k_{it} - \alpha_l^* \cdot l_{it} - \mathbf{x_{it}}\beta^*$$

The model assumes that $\Omega_{it}^{AFTER}$ moves according to an endogenous Markov process. Productivity considers the entirety of unobserved factors that can modify the volume heated by a DH firm when observable characteristics are kept constant. Moreover, I consider a process where the lagged level of capital quality is allowed to impact productivity of PPP firms and thus affects productivity changes as:

$$\omega_{it}^A = g(\omega_{it-1}^A,\, a_{it-1} * PPP_i) + \xi_{it} \tag{10}$$

i.e. productivity follows a first-order Markov process, where $g$ is a non-parametric function of $\omega_{it-1}^A$ and $a_{it-1} * PPP_i$. This process captures productivity changes due to investments on the capital quality level of PPP firms. When PPP firms update their expectation to a higher productivity level and have to decide about changes to the capital stock, they adjust their capital in order to retain the optimal capital quality.

The term $\xi_{it}$ is a shock to productivity between time $t-1$ and $t$, which is independent of the DH firm's time-t information set. The sample counterpart of the polynomial $g(.)$ is recovered by regressing $\widehat{\omega}_{it}$ on a polynomial of $\widehat{\omega}_{it-1}$ , which is used to identify the series of shocks

$$\xi_{it} = \widehat{\omega}_{it} - \widehat{g(.)}$$

exploiting the timing assumption about production, it is possible to construct a moment estimator using the following set of moment conditions:

$$E\begin{bmatrix} \xi_{it}\cdot l_{it-1} \\ \xi_{it}\cdot k_{it} \\ \xi_{it}\cdot a_{it} \\ \xi_{it}\cdot a_{it}PPP_i \\ \xi_{it}\cdot PPP_i \\ \xi_{it}\cdot d_i^n\ \forall n \\ \xi_{it}\cdot Cog_i \\ \xi_{it}\cdot Tech_i \\ \xi_{it}\cdot dTemp_{it} \\ \xi_{it}\cdot s_i^q\ \forall q \\ \xi_{it}\cdot 2014_t \end{bmatrix} = 0$$

standard errors are calculated through block bootstrap. Optimization is carried out through the Nelder-Mead algorithm and to ensure convergence, different starting points were tried. Finally, I recover TFP estimates as follows:

$$\widehat{\omega}_{it} = ed_{it} - \alpha_k^*\cdot k_{it} - \alpha_l^*\cdot l_{it} - \mathbf{x_{it}}\beta^* \tag{11}$$

# 5 Results

In table 6, I present the baseline estimates. In columns 1 and 2, I report a parsimonious version of the model without the capital quality terms, estimated using the least square (OLS) and the within (FE) estimators as benchmarks for the structural estimation. The point estimates are associated with clustered standard errors in parentheses. First, I consider the estimates of the inputs elasticities, $\alpha_k$ and $\alpha_l$. It is immediately evident that these parameters differ significantly across methods. In particular, a comparison between OLS and the FE reveals how severe the bias is when only the crossectional variation is used to identify input elasticities. Treating the same DH firm across time as several different observed units greatly affects the results since more productive firms are likely to use a greater quantity of the inputs. I find a biased down capital elasticity of OLS relative to FE estimator (0.37 vs 0.49). The FE estimator, on the other hand, exploits only the year-to-year variation in DH firms' inputs: estimation by FE accounts for the differences across DH firms, but these differences remain constant over time. I observe decreasing returns to scale as expected from the technical literature on DH plants, see Brännlund and Kristräm (2001), even after controlling for size dummies[20]. Moreover, the estimated coefficients are consistent with previous attempts of estimation of the marginal productivity of capital and labor in a valued-added production function context, see for reference the cited article of Brännlund and Kristräm (2001). In columns 3-4, I introduce the capital quality proxy and interaction with the procurement dummy, respectively. The effect of a unit increase in the capital quality per se is minimal, $-0.002$ , and the PPP dummy is not significantly different from zero. On the other hand, the interaction is significant and positive, and a unit increase of the capital quality for PPP firms increases the output by 11%.

In column 6, I present the results from the structural estimation procedure. The point estimates are associated with bootstrapped clustered standard errors in parentheses. I find that the simultaneity bias affects upward the capital marginal elasticity. A capital coefficient equal to 0.34 is in line with a capital-intensive industry such as DH, whereas a 1% increase in the labor input shifts up the output by 15% only. It is also in line with the hypothesis of restrained substitution between capital and thermal energy. These estimates can be compared with the Levinson and Petrin model in column 5 where the collinearity correction is not present and the estimates are strongly biased downward.

As for the effect of capital quality, I find an insignificant marginal effect of capital quality,

[20] Decreasing return to scale are not in contrast with a natural monopoly with U-shaped cost function.

$a_{it}$. It means that capital quality for non-PPP firms is a rather unproductive input. The explanation may be twofold. First, measurement error bias could explain it, but I am able to rule it out with further robustness checks. Second, the absence of a bundling phase does not allow for lower implementation costs, resulting in a less productive input for non-PPP firms. In this case, low variation remains that the size dummies and the other capital proxy, the number of heat-exchanger substations, cannot explain for non-PPP DH.

I find a strong and significant marginal effect on output of a quality investment in capital for PPP firms, the interaction term. In particular, reducing by one unit (negative) the length of the pipeline for every $100\,m^3$ of heated volume shifts up the expected change in log of output by 0.161 for PPP firms. In level terms, it corresponds to an output increase of 17%. Based on a back-of-the-envelope calculation, if the same mechanism of horizontal monitoring had been implemented for non-PPP firms, by setting the same level of capital quality as for PPPs, the increased output would have been 2922 MWh[21]. The same level of output, on the other hand, could have been sustained at the new level of capital quality by reducing thermal losses of the same amount, meaning an overall reduction in $CO^2$ emission of 1403 equivalent tons [22]. Unlike the OLS model, the structural model finds a significant positive effect of the PPP dummy of 0.133, which in level terms corresponds to a 14% increase in output.

among the control variables, in column 6, the co-generation dummy is strongly significant and positive, suggesting that the contemporaneous production of electricity and thermal energy affects the heat distribution thermal capacity of DH firms. Producing thermal energy without electricity decreases the average output by 47%. I find strong significant positive effects, equal to 0.391 and 0.440 respectively of the geographical dummies, in colder areas the average output is increased. A dummy for the hot winter of 2014 is negative and strongly significant that means a reduction of 36% of the average output in this period. Differences in

[21] The calculation is carried out in this way: the difference between PPP and non-PPP capital quality, $2.61 - 2.42$, times the marginal effect $\hat{\beta}_a$, 0.15, times the average distributed energy of non-PPP, 90480 $MWh$.

[22] I assume a conversion ratio between distributed thermal energy, MWh , and $CO^2$ emissions, equivalent tons, of 0.48. This value is estimated through a linear model.

average extracted temperature have no meaningful effect on the thermal energy distribution, likely due to the low variation across cities of the average capacity of buildings to absorb thermal energy.

# 6 Robustness checks

## Alternative approach and measurement error in quality

As a further robustness check, I propose the Wooldridge (2009) estimator. This estimator is robust to the criticism of Ackerberg et al. (2015) and can be constructed relying on either intermediate materials or investment to proxy for productivity. The literature refers to the former as the Wooldridge–LP and the latter as the Wooldridge–OP. The Wooldridge (2009) consists of a two-equation system GMM estimator, where the first equation accounts for the dynamic process of productivity, equation (10), and the second approximates the term $\Phi$. This estimator exploits moments on the vector error term:

$$E\begin{bmatrix} \xi_{it} & \\ & \mid I_{it} \\ \epsilon_{it} & \end{bmatrix} = 0$$

where $I_{it}$ is the usual information set of a DH firm $i$ at $t$. This approach avoids bootstrapping to obtain standard errors on the production function coefficients, since the two equations are jointly estimated in a single step. However, this procedure requires joint estimation of all polynomial coefficients of the unknown functions that approximate the dynamic process of productivity and the term $\Phi$, together with all production coefficients and the control variables. It implies a search over a larger parameter space than the ACF methodology since it is necessary to search jointly for the production function coefficients, the control variables coefficients, and all polynomial coefficients. To estimate all the parameters, it requires reducing the polynomial degree (I use a 2nd order), which reduces the precision. Moreover, the basic Wooldridge estimator does not account for a complex law of motion of productivity. The basic version of this estimator proxies the law of motion of productivity through a random walk. In table 7, I report the estimates. In the first column, I used the intermediate material as proxy. The elasticitiy estimates for the capital and labor inputs are smaller than the two-stage model estimates , and in particular the labor input coefficient goes to zero. Focusing on the PPP effect, the interaction term $\beta_{int}$ has a positive and significant effect of 0.122, consistent with the baseline model estimates. A unit increase in capital quality increases the output in level terms by 11%. The PPP dummy is positive, but not significant.

The high quality of the data ensures no bias problems due to measurement error for output and input proxies. However, the proxy $a_{it}$ is an indirect measure of the design quality of the plant, and a value of $\hat{\beta}_a$ proximal to zero induces some doubts over it. In column 2, I implement the Collard-Wexler and De Loecker (2016) variant of the Wooldridge estimator, which is specifically thought to solve the problem of measurement error for the capital input. The idea is to use investment not as a proxy variable for technical efficiency $\omega$, but as an instrument for the stock of capital and, in my case, for capital quality. For this purpose, you have to instrument all the polynomial terms containing the capital quality with the first and second lags. To instrument, I use both the yearly variation in the pipeline's length and the substations number. In this case, the investment does not enter the control function, and the zero observations do not pose any theoretical problem of inversion. In the CD estimator case, the elasticity estimates are closer to the same parameters estimated with the two-stage model. The most significant difference relates to the capital quality parameters. A possible measurement error correction makes the PPP and the interaction term overshooting but does not move the capital quality parameter from zero.

## Translog production function

In order to check how misspecifications of the functional form of the production function can affect the estimates, I consider the following "structural value added" translog production function:

$$ed_{it} = \alpha_k k_{it} + \alpha_l l_{it} + \alpha_{kk} k_{it}^2 + \alpha_{ll} l_{it}^2 + \alpha_{kl} k_{it} l_{it} + \mathbf{x_{it}}\beta + \omega_{it} + \epsilon_{it}$$

the translog production function approximates a CES production function with a second-order Taylor series. Differently from the Cobb-Douglas production function, translog does not assume "smooth" substitution between production factors. In addition, the family of translog production functions includes the linear additivity among inputs as a special case of the nonlinear ones.

The first-stage polynomial is not affected by this different production function form since the squared and the interaction term are already included. Similarly, I can recover the residual $\xi_{it}$ from the non-parametric equation of the dynamic process of $\omega_{it}$ and use it to construct the new moment conditions:

$$E\begin{bmatrix} \xi_{it} \cdot l_{it-1} \\ \xi_{it} \cdot k_{it} \\ \vdots \\ \xi_{it} \cdot l_{it-1}^2 \\ \xi_{it} \cdot k_{it}^2 \\ \xi_{it} \cdot k_{it} l_{it-1} \\ \vdots \\ \xi_{it} \cdot s_i^q \ \forall q \\ \xi_{it} \cdot 2014_t \end{bmatrix} = 0$$

in Table 8, I replicate the specifications of Table 6 by employing the translog production function. In the last column, both the PPP dummy and the interaction with the capital quality remain positive and significant. Their effect on output is slightly larger, by 0.167 and 0.149, respectively, for the PPP dummy and the interaction term. The estimated input elasticities are a linear combination of the estimated coefficients of the production function. The inputs elasticities for the capital and labor inputs are given by:

$$\hat{\theta}_{kit} = \hat{\alpha}_k + 2\hat{\alpha}_{kk}k_{it} + \hat{\alpha}_{kl}l_{it}$$

$$\hat{\theta}_{lit} = \hat{\alpha}_l + 2\hat{\alpha}_{ll}l_{it} + \hat{\alpha}_{kl}k_{it}$$

in Table 9, I report the calculated elasticities in terms of averages of three different models: the simple OLS, the fixed-effect and the control function approach models. Both OLS and fixed-effects show upward bias for capital elasticity. Furthermore, the estimates are in line with what I find under the Cobb-Douglas specification regarding bias direction. The flexible translog highlights the severe downward bias problem of the labor coefficient, which increases up to 0.20.

## More dummies

As a further robustness check, I verify how the structure of the size dummies affects the estimates. I propose two different specifications. The first considers a more complex structure of dummies, in deciles of the heated volume distribution. The second directly uses the continuous variable. Estimations are reported in Table 10. In column 3, the magnitude of the interaction term is strengthened by the presence of a more dense structure of the dummies. A unit change in capital quality increases log output by 0.263, which in level terms means a 30% increase in output. Moreover, the PPP dummy continues to be positive and significant, with an effect similar to the baseline specification. In column 6, the model is augmented with a continuous variable controlling for the household heated volume. Estimates of the interaction term remain similar to the model with a deeper structure of dummies, but the PPP dummy loses its effect. Both the specifications in columns 3 and 6 show smaller estimates of labor elasticity with respect to the baseline model. Measurement error in labor could be the reason for the variability in labor elasticity estimates.

### Selection due to procurement choice

A possible concern about the correct estimation of the technical efficiency parameter is the selection induced by the procurement scheme's choice. To tackle this issue, I extend the model with a further step, where the law of motion of technical efficiency in 10 includes a correction term. Olley and Pakes (1996) employ a similar approach to deal with selection of firms due to attrition. The correction term is a non parametric estimate of the probability of each public body choosing PPP. This probability is defined as:

$$Pr_j\left(PPP = 1|\mathbf{I}^{\mathbf{Public\,Body}}\right)$$

where the function is the probability of public bodies, $j$, choosing PPP against traditional procurement conditional on the information set $\mathbf{I}^{\mathbf{Public\,Body}}$. This probability is estimated through a probit regression of each public body's procurement choice on the population of each municipality and area and time fixed effect, plus a flexible polynomial of the fiscal efficiency proxy. Not all the municipalities have made their balance sheets available, reducing the dimension of the sample. The identifying exclusion restriction is that more competent municipalities, identified through higher fiscal efficiency levels, will be more likely to use a complex instrument as PPP.

The estimates of the exclusion restriction from the first-stage probit are reported in the bottom panel of table 11. The exclusion restriction is slightly significant, and this is evidence for possible selection. In column 1 of the top panel, I report estimates of the main baseline model, but constrained to the reduced sample for comparison. In column 2, I present the model with the probability prediction as a stand-alone control variable, which is positive and significant. In column 3, I present the augmented model. I find smaller input elasticities for the capital input, and capital quality, $a$, becomes slightly negative significant. The PPP dummy and the interaction with the quality dummy remain positive and significant, with an even greater effect. These effects can result from the reduction of sample dimension, and the negative capital quality effect results more than compensated under PPP.

## Selection due to costly participation

Another possible concern is the bias induced by a selective procurement stage held before production. A noisy signal that private sellers receive from buyers could invalidate the estimation strategy by selecting participants in the tender. This article moves in an intermediate world between the Samuelson (1985) model, where each potential entrant knows its independent private value before the entry decision, so the selection is perfect, and the Levin and Smith (1994) model, where a potential entrant only knows the distribution from which her value is drawn. To tackle this issue, I augment the law of motion of technical efficiency in equation (10) with a correction term for the probability $Pr_i(\mathbf{I}^{\mathbf{Project}})$ of each winner entering the competition. This probability is defined as:

$$Pr_i(\mathbf{I}^{\mathbf{Project}}) = \begin{cases} Pr_i(Entry = 1|\mathbf{I}^{Project}) & if\, competed = 1 \\ 1 & otherwise \end{cases}$$

where the function $Pr_i(Entry = 1|\mathbf{I}^{Project})$ is the conditional probability of potential entrant, $z$, entering in a competed tender given the information set $\mathbf{I}^{Project}$. The sample enumerates a 79% of tenders that are not competed, where the DH management is provided in-house. I add a control for this feature. Obviously, in-house firms have probability equal to 1 of entering. For tenders that are competed, the probability $Pr_i(Entry = 1|\mathbf{I}^{Project})$

is estimated through a first-step probit regression of the entry decision of each potential entrant on project and contract characteristics, plus a flexible polynomial of the number of other entrants. A potential set of entrants for each tender is obtained through a detailed and accurate research of company profiles and collection of data on previous projects and areas of activity. For each contract, I assign to the set of potential entrants any company active at the time and in the same province where the contract was awarded. Due to the inefficiency of the Italian authorities in collecting procurement data, not all the contracts are available. I use all the available contracts to train the probit model. The identifying exclusion restriction is that potential competition affects a bidder's decision to enter an auction, but has no direct effect on values, as in Roberts and Sweeting (2016). The estimates of the exclusion restriction from the first-stage probit are reported in the bottom panel of table 12. The exclusion restriction is strongly significant, and this is evidence for possible selection.

In the top panel, Column 1 reports model estimates in column 6 of table 6 for comparison. In column 2, I introduce the in-house control and in column 3 the augmented model with a further stage controlling for the probability of each winner entering the competition. I find similar input elasticities for the capital input, but smaller estimates for the labor input. The PPP dummy and the interaction with the quality dummy remain positive and significant, with an even greater effect. In general, the estimates are very close.

# 7 Conclusion

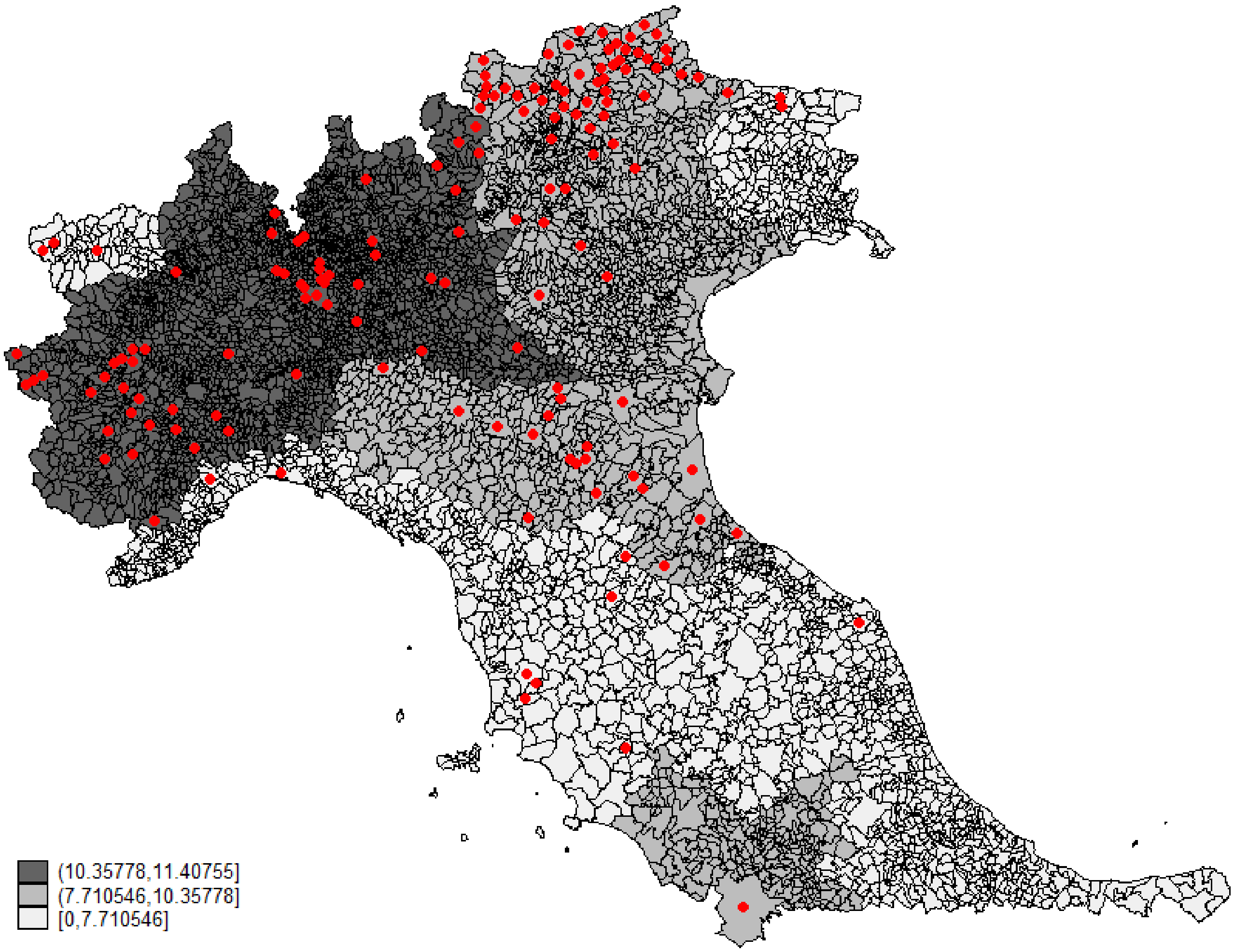
The long-debated cost-reducing effect of PPPs has been questioned because cost increases and quality dispersion have often been reported for PPP projects. This work sheds light on the role that capital quality plays. To test this effect, I exploited the combination of PPP and the DH sector as the environment. I made use of high-quality data with detailed information on the entire production process, measuring each variable of interest in physical quantities. It avoids confounding factors due to unobserved prices of inputs and outputs. I used a structural model to separately identify the externality mechanism from the residual part of TFP. The model is robust to simultaneity and multicollinearity problems.

I find evidence for the existence of the PPP efficiency effect, which has a significant and positive effect on productivity. The channel of this effect is the quality of capital input that the PPP allows to be more productive. The effect per se is striking; reducing the length of the pipeline by one meter for every $100\,m^3$ of heated volume, raises the expected change in log of output between 0.142 and 0.263 across different specifications. At the same time, the effect of capital quality for non-PPP firms is not distinguishable from zero in the different specifications, while the positive effects of PPP unrelated to capital quality are not always present in all specifications. I performed several robustness checks that ensure the stability of the results with respect to misspecification of the production function, the presence of multiple local minima, and measurement error.

The results are robust to selection. Several proxies for corruption were found to be unrelevant. Greater competence of public entities appears to drive the choice of PPP as a procurement tool, but is not a confounder of the efficiency effect. Potential competition during the bidding phase shows a similar pattern. Selection, although present, does not significantly affect the estimates.

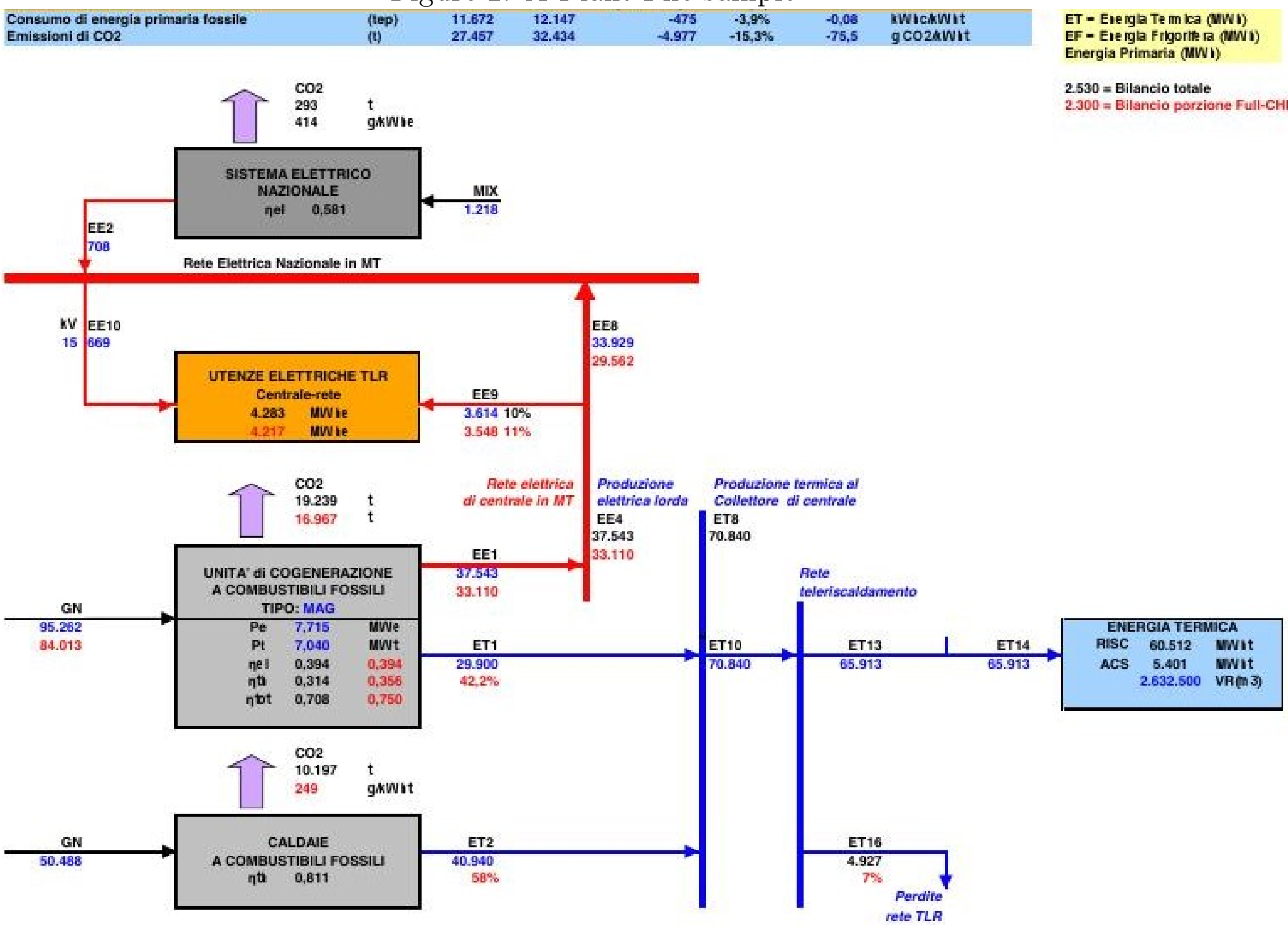
# 8 Tables and Figures

Figure 1: Plants distribution & total heated volume (log m3)




*Notes*: Geographical distribution of district heating plants. Colors represent the tertiles of the distributed thermal energy (white 1st tertile to dark grey, 3rd tertile).

Figure 2: A Plant File sample




*Notes*: The above figure is a sample file of the data provided by Airu. Each file is a detailed scheme of the production process of each plant.

Table 1: Summary statistics

| | Mean | Median | Standard Dev. | Iqr |
|---|---|---|---|---|
| **Non-PPP** | | | | |
| Distributed thermal energy, MWh | 90484.34 | 22255.99 | 257516.74 | 54189.98 |
| Heat Energy lost, MWh | 40423.89 | 3201.00 | 749589.25 | 6894.00 |
| Pipeline Length, m | 28447.37 | 10000.00 | 64925.87 | 17116.00 |
| Heat Exchanger Substations | 510.08 | 111.00 | 2024.79 | 327.50 |
| Average Temp extracted, c° | 30.56 | 25.00 | 12.52 | 15.00 |
| Cogeneration | 0.76 | 1.00 | 0.43 | 0.00 |
| Steam Heat vehicle | 0.58 | 1.00 | 0.49 | 1.00 |
| between 1400-2100 GG | 0.11 | 0.00 | 0.31 | 0.00 |
| between 2100-3000 GG | 0.53 | 1.00 | 0.50 | 1.00 |
| above 3000 GG | 0.36 | 0.00 | 0.48 | 1.00 |
| Number of Workers | 67.85 | 6.69 | 199.41 | 65.83 |
| Total heated volume, $10^3\,m^3$ | 2466.65 | 504.70 | 7036.03 | 1583.88 |
| $CO^2$, tons | 38249.48 | 5699.00 | 142797.02 | 19592.00 |
| **PPP** | | | | |
| Distributed thermal energy, MWh | 46689.48 | 19446.72 | 62238.70 | 41491.98 |
| Heat Energy lost, MWh | 8188.78 | 4304.16 | 9902.58 | 9193.00 |
| Pipeline Length, m | 24012.00 | 11000.00 | 30339.96 | 24500.00 |
| Heat Exchanger Substations | 449.05 | 165.00 | 616.33 | 400.00 |
| Average Temp extracted, c° | 29.36 | 25.00 | 11.53 | 12.00 |
| Cogeneration | 0.95 | 1.00 | 0.21 | 0.00 |
| Steam Heat vehicle | 0.32 | 0.00 | 0.47 | 1.00 |
| between 1400-2100 GG | 0.00 | 0.00 | 0.00 | 0.00 |
| between 2100-3000 GG | 0.86 | 1.00 | 0.35 | 0.00 |
| above 3000 GG | 0.14 | 0.00 | 0.35 | 0.00 |
| Number of Workers | 12.85 | 4.25 | 17.82 | 4.68 |
| Total heated volume, $10^3\,m^3$ | 1270.55 | 740.48 | 1443.03 | 1632.33 |
| $CO^2$, tons | 11358.98 | 3345.00 | 16442.92 | 11138.00 |
| **Total** | | | | |
| Distributed thermal energy, MWh | 86487.42 | 22255.99 | 246501.47 | 53704.99 |
| Heat Energy lost, MWh | 37674.17 | 3252.50 | 716924.50 | 7299.00 |
| Pipeline Length, m | 28070.51 | 10000.00 | 62732.56 | 17600.00 |
| Heat Exchanger Substations | 504.89 | 119.00 | 1945.02 | 343.00 |
| Average Temp extracted, c° | 30.45 | 25.00 | 12.43 | 15.00 |
| Cogeneration | 0.78 | 1.00 | 0.42 | 0.00 |
| Steam Heat vehicle | 0.56 | 1.00 | 0.50 | 1.00 |
| between 1400-2100 GG | 0.10 | 0.00 | 0.30 | 0.00 |
| between 2100-3000 GG | 0.55 | 1.00 | 0.50 | 1.00 |
| above 3000 GG | 0.35 | 0.00 | 0.48 | 1.00 |
| Number of Workers | 62.91 | 5.92 | 190.96 | 64.69 |
| Total heated volume, $10^3\,m^3$ | 2377.80 | 508.74 | 6787.89 | 1588.00 |
| $CO^2$, tons | 35514.07 | 5681.00 | 135670.27 | 16916.00 |

*Notes*: The Last panel presents summary statistics for the pooled set of plants (PPP and non-PPP plants). Distributed thermal and lost thermal energy are expressed in megawatt per hour (MWh). The heating degree-days (GG) dummies, follow the European standard EN ISO 15927-6. All variables are described in the main text.

Table 2: PPP market shares

| | 2002-2013 | |
|---|---|---|
| | # PPP won | Market share % (100=326.47 mln) |
| SIRAM SPA ( Veolia ) | 1 | 18.38% |
| Hera | 1 | 9.95% |
| ATZWANGER SPA | 1 | 8.21% |
| A2A SPA | 3 | 6.46% |
| Egea SPA | 4 | 5.27% |
| METANALPI ENERGIA SRL | 1 | 5.05% |
| T.E.S.I. SRL | 1 | 3.19% |
| % share of PPP market | | 56.51% |

*Notes*: Market shares of the PPP segment in terms of the base value of the contracts. 100 is the total value of the market.

Table 3: non-PPP market

| | 2002-2013 | |
|---|---|---|
| | # non-PPP won | Market share % (100=4244 mln) |
| HERA SPA | 9 | 9.07% |
| COFELY | 10 | 8.55% |
| A2A SPA | 5 | 6.49% |
| Egea SPA | 8 | 5.94% |
| ATZWANGER SPA | 1 | 5.19% |
| METANALPI ENERGIA SRL | 4 | 5.18% |
| SIRAM SPA (Veolia) | 4 | 3.90% |
| T.E.S.I. SRL | 5 | 3.21% |
| % share of non-PPP market | | 47.53% |

*Notes*: Market shares of the non-PPP segment in terms of the base value of the contracts. 100 is the total value of the market.

Table 4: PPP determinants

| | LPM | Probit | LPM | Probit | LPM | Probit |
|---|---|---|---|---|---|---|
| Fiscal Efficiency | 0.426** | 0.580** | 0.396** | 0.589** | 0.394** | 0.613** |
| | (0.182) | (0.241) | (0.175) | (0.259) | (0.174) | (0.251) |
| Corruption Proxy 1 | -0.177 | -0.230 | | | | |
| | (0.118) | (0.157) | | | | |
| Corruption Proxy 2 | | | -0.001 | -0.000 | | |
| | | | (0.001) | (0.001) | | |
| Corruption Proxy 3 | | | | | 0.002 | 0.008 |
| | | | | | (0.021) | (0.021) |
| Pop. 2006 | 0.123* | 0.184* | 0.115 | 0.087 | 0.055 | 0.052 |
| | (0.063) | (0.103) | (0.105) | (0.075) | (0.113) | (0.091) |
| N | 95 | 67 | 98 | 81 | 98 | 81 |

*Notes*: Corruption Proxy 1 is the stock of corruption measured by Golden Picci Index. Corruption Proxy 2 is the number of public workers denounced for corruption. Corruption Proxy 3 is the number of procurement experts denounced for corruption. Standard errors are robust. All models include controls for population level. * Significant at the 10 percent level; ** significant at the 5 percent level; *** significant at the 1 percent level.

Table 5: Tenders dynamic

| | 2007-2013 | | | |
|---|---|---|---|---|
| non-PPP phases | non-PPP<br>Average bids / (SD) | n | PPP<br>Average bids / (SD) | n |
| Operating managment | 2.14 | 7 | 4.08 | 13 |
| | (2.90) | | (5.99) | |
| Mantainance | 5.33 | 6 | ⋱ | ⋱ |
| | (1.48) | | ⋱ | |
| Building | 8.71 | 7 | ⋱ | ⋱ |
| | (6.80) | | ⋱ | |

*Notes*: The table reports the average number of bids made in PPP tenders along with the average number of bids for building, operating and maintenance in non-PPP tenders. A non-directional t-test (t-statistics equal to 0.77 with 31 degree of freedom) confirms that the difference between the means of two independent samples is not statistically different from zero.

Table 6: Model Estimates

| | Restricted Model | | Augmented Model | | | |
|---|---|---|---|---|---|---|
| | OLS | FE | OLS | OLS | LP | ACF |
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Number of workers, L | 0.054 | 0.003 | 0.055 | 0.052 | -0.010 | 0.152** |
| | (0.031) | (0.026) | (0.031) | (0.031) | (0.027) | (0.049) |
| Number of Substations, K | 0.371*** | 0.490*** | 0.370*** | 0.379*** | 0.234 | 0.340*** |
| | (0.048) | (0.117) | (0.048) | (0.046) | (0.179) | (0.050) |
| Capital Quality, $a$ | | | -0.002* | -0.002* | -0.002 | -0.085 |
| | | | (0.001) | (0.001) | (0.023) | (0.057) |
| PPP contract | | | | -0.046 | -0.841 | 0.133*** |
| | | | | (0.182) | (0.804) | (0.040) |
| PPP $*$ Capital Quality, $a$ | | | | 0.104*** | 0.091 | 0.161*** |
| | | | | (0.031) | (0.336) | (0.046) |
| Cogeneration dummy, Cog | 0.406** | 0.149 | 0.404** | 0.437** | 0.551* | 0.427*** |
| | (0.135) | (0.180) | (0.135) | (0.132) | (0.271) | (0.039) |
| Heat vehicle dummy, Tech | 0.492*** | 0.093 | 0.491*** | 0.464*** | 0.274* | 0.416*** |
| | (0.115) | (0.084) | (0.116) | (0.119) | (0.114) | (0.038) |
| Zone 2 | 0.509* | 0.091 | 0.510* | 0.524* | 0.223 | 0.391*** |
| | (0.235) | (0.139) | (0.235) | (0.238) | (0.191) | (0.042) |
| Zone 3 | 0.530* | 0.266 | 0.532* | 0.542* | 0.262 | 0.440*** |
| | (0.241) | (0.197) | (0.241) | (0.242) | (0.269) | (0.042) |
| 2014 dummy | -0.351*** | -0.262* | -0.355*** | -0.350*** | -0.436*** | -0.308*** |
| | (0.101) | (0.106) | (0.102) | (0.101) | (0.118) | (0.065) |
| Extracted Temperature, dTemp | 0.003 | 0.010 | 0.003 | 0.003 | 0.022 | 0.004 |
| | (0.006) | (0.007) | (0.006) | (0.006) | (0.013) | (0.018) |
| Small (<p25) | -0.943*** | -0.227 | -0.950*** | -0.911*** | -0.649* | -0.976*** |
| | (0.142) | (0.218) | (0.142) | (0.142) | (0.328) | (0.046) |
| Big (p75<>p50) | 0.649*** | 0.348* | 0.650*** | 0.660*** | 0.220 | 0.667*** |
| | (0.133) | (0.167) | (0.133) | (0.133) | (0.179) | (0.040) |
| Very Big (>p75) | 1.410*** | 0.433** | 1.415*** | 1.411*** | 0.223 | 1.381*** |
| | (0.193) | (0.165) | (0.194) | (0.189) | (0.246) | (0.045) |
| N | 742 | 742 | 742 | 742 | 742 | 742 |

*Notes*: Columns 1-2 report reduced-form regressions of the production function estimated using least square and within estimators. Column 3 introduces the proxy for capital quality. In column 4, the model is augmented with the structural terms and estimated through OLS. Column 5 reports the estimates of the structural model using the static input as control proxy without controlling for collinearity in inputs. In column 6, the estimates of the structural model with the collinearity correction are reported. Among the controls, Zone 2 is defined between 2100-3000 GG and Zone 3 above 3000 GG. The model standard errors are block bootstrapped and clustered at plant level. The capital quality proxy and the interaction term with the PPP dummy have an inverted sign such that increasing values correspond to higher levels of quality. * Significant at the 10 percent level; ** significant at the 5 percent level; *** significant at the 1 percent level.

Table 7: Robustness Checks: Wooldridge estimator

| | Wooldridge (1) | CD (2) |
|---|---|---|
| Number of workers, L | -0.013 | 0.139** |
| | (0.036) | (0.046) |
| Number of Substations, K | 0.278*** | 0.404* |
| | (0.097) | (0.163) |
| Capital Quality, $a$ | -0.002*** | -0.028 |
| | (0.001) | (0.027) |
| PPP contract | 0.040 | 1.227* |
| | (0.144) | (0.487) |
| PPP $*$ Capital Quality, $a$ | 0.122** | 0.686** |
| | (0.048) | (0.234) |
| Cogeneration dummy, Cog | 0.369** | 0.552* |
| | (0.144) | (0.224) |
| Heat vehicle dummy, Tech | 0.284*** | 0.005 |
| | (0.074) | (0.110) |
| Zone 2 | 0.124 | 0.320 |
| | (0.188) | (0.260) |
| Zone 3 | 0.073 | 0.343 |
| | (0.224) | (0.312) |
| 2014 dummy | -0.400*** | -0.386*** |
| | (0.100) | (0.107) |
| Extracted Temperature, dTemp | 0.004 | 0.027** |
| | (0.005) | (0.008) |
| Small (<p25) | -0.677*** | -0.215 |
| | (0.137) | (0.208) |
| Big (p75<>p50) | 0.496** | 0.310 |
| | (0.153) | (0.171) |
| Very Big (>p75) | 0.888*** | 0.532* |
| | (0.212) | (0.259) |
| N | 741 | 603 |

*Notes*: Column 1 reports the single step Wooldridge estimator that employs intermediate material as a proxy variable. Column 3 reports the augmented model that accounts for measurement error in capital quality, the WexCollard-DeLocker estimator. Among the controls, Zone 2 is defined between 2100-3000 GG and Zone 3 above 3000 GG. The standard errors are clustered at plant level. The capital quality proxy and the interaction term with the PPP dummy have an inverted sign such that increasing values correspond to higher levels of quality. * Significant at the 10 percent level; ** significant at the 5 percent level; *** significant at the 1 percent level.

Table 8: Robustness Checks: Translog specification

| | Restricted Model | | Augmented Model | | |
|---|---|---|---|---|---|
| | OLS | FE | OLS | OLS | ACF |
| | (1) | (2) | (3) | (4) | (5) |
| Number of workers, L: | | | | | |
| 1st degree term | -0.033 | 0.020 | -0.033 | -0.031 | -0.047*** |
| | (0.078) | (0.085) | (0.078) | (0.078) | (0.010) |
| 2nd degree term | 0.003 | -0.004 | 0.003 | 0.001 | 0.010 |
| | (0.008) | (0.005) | (0.008) | (0.009) | (0.014) |
| Number of Substations, K: | | | | | |
| 1st degree term | 0.023 | 1.016** | 0.017 | 0.017 | -0.156*** |
| | (0.109) | (0.498) | (0.110) | (0.107) | (0.008) |
| 2nd degree term | 0.033*** | -0.063 | 0.033*** | 0.034*** | 0.037*** |
| | (0.011) | (0.051) | (0.011) | (0.011) | (0.012) |
| Interaction term | 0.015 | -0.001 | 0.015 | 0.016 | 0.045** |
| | (0.018) | (0.016) | (0.018) | (0.018) | (0.021) |
| Capital Quality, $a$ | | | -0.002*** | -0.002*** | -0.021 |
| | | | (0.001) | (0.001) | (0.019) |
| PPP contract | | | | -0.013 | 0.167*** |
| | | | | (0.177) | (0.009) |
| PPP $*$ Capital Quality, $a$ | | | | 0.114*** | 0.149*** |
| | | | | (0.027) | (0.012) |
| Cogeneration dummy, Cog | 0.426*** | 0.096 | 0.424*** | 0.454*** | 0.472*** |
| | (0.132) | (0.169) | (0.133) | (0.129) | (0.010) |
| Heat vehicle dummy, Tech | 0.413*** | 0.088 | 0.412*** | 0.383*** | 0.392*** |
| | (0.110) | (0.091) | (0.110) | (0.112) | (0.011) |
| Zone 2 | 0.431* | 0.093 | 0.432* | 0.443* | 0.382*** |
| | (0.239) | (0.136) | (0.239) | (0.242) | (0.012) |
| Zone 3 | 0.475* | 0.284 | 0.477* | 0.488* | 0.460*** |
| | (0.248) | (0.196) | (0.248) | (0.248) | (0.014) |
| 2014 dummy | -0.333*** | -0.252** | -0.339*** | -0.335*** | -0.326*** |
| | (0.100) | (0.105) | (0.101) | (0.100) | (0.012) |
| Extracted Temperature, dTemp | 0.004 | 0.009 | 0.004 | 0.004 | 0.022* |
| | (0.006) | (0.007) | (0.006) | (0.006) | (0.011) |
| Small (<p25) | -1.011*** | -0.146 | -1.021*** | -0.982*** | -0.989*** |
| | (0.142) | (0.210) | (0.142) | (0.143) | (0.015) |
| Big (p75<>p50) | 0.721*** | 0.353** | 0.724*** | 0.735*** | 0.775*** |
| | (0.130) | (0.163) | (0.130) | (0.130) | (0.011) |
| Very Big (>p75) | 1.388*** | 0.483*** | 1.394*** | 1.390*** | 1.444*** |
| | (0.193) | (0.162) | (0.193) | (0.188) | (0.009) |
| N | 742 | 742 | 742 | 742 | 742 |

*Notes*: Columns 1-2 report reduced-form regressions of the production function estimated using least square and within estimators. Column 3 introduces the proxy for capital quality. In Column 4, the model is augmented with the structural terms. In Column 5, the estimates of the structural model are reported with the collinearity correction. The controls, Cogeneration dummy, 2014 dummy, Extracted Temperature, Zone 2 and Zone3 variables are omitted for readability purpose. The model standard errors are block bootstrapped and clustered at plant level. The capital quality proxy and the interaction term with the PPP dummy have an inverted sign such that increasing values correspond to higher levels of quality. * Significant at the 10 percent level; ** significant at the 5 percent level; *** significant at the 1 percent level.

Table 9: Average Translog Elasticities

| | Capital | Labour |
|---|---|---|
| Model | .2949 | .2139 |
| OLS | .3743 | .0484 |
| Fe | .4239 | -.0019 |

*Notes*: I report the averages of the output elasticities to capital and labor inputs from the predicted values of three different estimator of the translog production function: the OLS, the fixed-effects and the control function approach models.

Table 10: Robustness Checks: Dummies

| | Discrete Dummies | | | Continous Heated Volume | | |
|---|---|---|---|---|---|---|
| | OLS | LP | ACF | OLS | LP | ACF |
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Number of workers, L | 0.042* | 0.014 | 0.068 | 0.021 | -0.001 | 0.108 |
| | (0.018) | (0.023) | (0.064) | (0.017) | (0.023) | (0.087) |
| Number of Substations, K | 0.329*** | 0.187 | 0.318*** | 0.271*** | 0.341* | 0.311*** |
| | (0.022) | (0.155) | (0.054) | (0.022) | (0.161) | (0.093) |
| Capital Quality, $a$ | -0.004* | -0.004 | -0.139 | -0.007*** | -0.002 | -0.153 |
| | (0.002) | (0.024) | (0.074) | (0.002) | (0.026) | (0.090) |
| PPP contract | -0.165 | -0.304 | 0.122* | -0.153 | -0.742 | -0.017 |
| | (0.151) | (0.703) | (0.051) | (0.147) | (0.569) | (0.095) |
| PPP $*$ Capital Quality, $a$ | 0.069 | -0.013 | 0.243*** | 0.034 | -0.099 | 0.263** |
| | (0.045) | (0.147) | (0.052) | (0.044) | (0.135) | (0.083) |
| Cogeneration dummy, Cog | 0.368*** | 0.261 | 0.437*** | 0.394*** | 0.612* | 0.310** |
| | (0.079) | (0.245) | (0.049) | (0.075) | (0.286) | (0.104) |
| Heat vehicle dummy, Tech | 0.310*** | 0.198 | 0.264*** | 0.206** | 0.224* | 0.264** |
| | (0.083) | (0.124) | (0.055) | (0.078) | (0.110) | (0.083) |
| Zone 2 | 0.381** | 0.233 | 0.412*** | 0.233* | 0.179 | 0.312*** |
| | (0.116) | (0.251) | (0.051) | (0.112) | (0.163) | (0.094) |
| Zone 3 | 0.371** | 0.152 | 0.301*** | 0.259* | 0.129 | 0.287** |
| | (0.131) | (0.305) | (0.062) | (0.125) | (0.295) | (0.099) |
| 2014 dummy | -0.330*** | -0.427*** | -0.356*** | -0.299*** | -0.437*** | -0.381*** |
| | (0.072) | (0.115) | (0.077) | (0.071) | (0.107) | (0.089) |
| Extracted Temperature, dTemp | 0.006 | 0.023 | 0.012 | 0.009* | 0.012 | 0.023 |
| | (0.004) | (0.013) | (0.023) | (0.004) | (0.014) | (0.026) |
| N | 742 | 742 | 742 | 742 | 742 | 742 |

*Notes*: Columns 1-3 report estimates of the structural production function estimated through OLS and the two-step procedure with and without the correction for collinearity in inputs. The size dummies are in terms of deciles of the heated volume distribution. In columns 4-6, I use the continuous variable. Among the other controls, Zone 2 is defined between 2100-3000 GG and Zone 3 above 3000 GG. The model standard errors are block bootstrapped and clustered at plant level. The capital quality proxy and the interaction term with the PPP dummy have an inverted sign such that increasing values correspond to higher levels of quality. * Significant at the 10 percent level; ** significant at the 5 percent level; *** significant at the 1 percent level.

Table 11: Robustness Checks: PPP choice

| | (1) | (2) | (3) |
|---|---|---|---|
| Number of workers, L | 0.095 | 0.104 | 0.132 |
| | (0.072) | (0.077) | (0.078) |
| Number of Substations, K | 0.192* | 0.204** | 0.171* |
| | (0.078) | (0.066) | (0.067) |
| Capital Quality, $a$ | -0.149 | -0.167 | -0.164* |
| | (0.090) | (0.086) | (0.083) |
| PPP contract | 0.300*** | 0.377*** | 0.359*** |
| | (0.075) | (0.062) | (0.061) |
| PPP $*$ Capital Quality, $a$ | 0.168* | 0.142* | 0.200** |
| | (0.067) | (0.067) | (0.071) |
| Cogeneration dummy, Cog | 0.412*** | 0.526*** | 0.583*** |
| | (0.083) | (0.068) | (0.070) |
| Heat vehicle dummy, Tech | 0.016 | 0.098 | 0.094 |
| | (0.060) | (0.064) | (0.064) |
| Zone 2 | 0.260*** | 0.191** | 0.250*** |
| | (0.078) | (0.073) | (0.073) |
| Zone 3 | 0.507*** | 0.452*** | 0.357*** |
| | (0.073) | (0.073) | (0.066) |
| 2014 dummy | -0.417*** | -0.417*** | -0.294** |
| | (0.121) | (0.112) | (0.105) |
| Extracted Temperature, dTemp | 0.022 | 0.026 | 0.024 |
| | (0.025) | (0.024) | (0.027) |
| Small (<p25) | -0.819*** | -0.751*** | -0.839*** |
| | (0.088) | (0.069) | (0.081) |
| Big (p75<>p50) | 0.583*** | 0.569*** | 0.666*** |
| | (0.078) | (0.071) | (0.073) |
| Very Big (>p75) | 1.472*** | 1.199*** | 1.216*** |
| | (0.107) | (0.069) | (0.091) |
| PPP choice Probability | | 1.044*** | |
| | | (0.066) | |
| Fiscal Efficiency | | -.21* | -.21* |
| sq. Fiscal Efficiency | | .61 | .61 |
| N | 362 | 362 | 362 |

*Notes*: Top panel. Column 1 reports the baseline model estimated with a constrained sample for comparison. In column 2, I introduce the municipalities' probability of choosing the procurement form as control and in column 3 the augmented model with the probability added to the law of motion. Among the other controls, Zone 2 is defined between 2100-3000 GG and Zone 3 above 3000 GG. The model standard errors are block bootstrapped and clustered at plant level. The capital quality proxy and the interaction term with the PPP dummy have an inverted sign such that increasing values correspond to higher levels of quality. Bottom panel. The probit model regress a PPP choice dummy on municipality's characteristics, area and time fixed effects and a suitable 2nd degree polynomial in the fiscal efficiently measure. * Significant at the 10 percent level; ** significant at the 5 percent level; *** significant at the 1 percent level.

Table 12: Robustness Checks: Costly Participation

| | (1) | (2) | (3) |
|---|---|---|---|
| Number of workers, L | 0.152** | 0.132** | 0.072 |
| | (0.049) | (0.050) | (0.045) |
| Number of Substations, K | 0.340*** | 0.382*** | 0.370*** |
| | (0.055) | (0.046) | (0.049) |
| Capital Quality, $a$ | -0.085 | -0.025 | -0.004 |
| | (0.057) | (0.062) | (0.056) |
| PPP contract | 0.133*** | 0.122** | 0.147*** |
| | (0.035) | (0.041) | (0.033) |
| PPP $*$ Capital Quality, $a$ | 0.161*** | 0.113** | 0.176*** |
| | (0.036) | (0.042) | (0.042) |
| Cogeneration dummy, Cog | 0.427*** | 0.361*** | 0.448*** |
| | (0.042) | (0.041) | (0.036) |
| Heat vehicle dummy, Tech | 0.416*** | 0.468*** | 0.466*** |
| | (0.037) | (0.041) | (0.039) |
| Zone 2 | 0.391*** | 0.454*** | 0.463*** |
| | (0.045) | (0.041) | (0.038) |
| Zone 3 | 0.440*** | 0.503*** | 0.503*** |
| | (0.043) | (0.042) | (0.041) |
| 2014 dummy | -0.308*** | -0.420*** | -0.372*** |
| | (0.066) | (0.066) | (0.062) |
| Extracted Temperature, dTemp | 0.004 | 0.009 | 0.013 |
| | (0.018) | (0.018) | (0.016) |
| Small (<p25) | -0.976*** | -0.928*** | -0.934*** |
| | (0.041) | (0.044) | (0.039) |
| Big (p75<>p50) | 0.667*** | 0.620*** | 0.618*** |
| | (0.035) | (0.043) | (0.040) |
| Very Big (>p75) | 1.381*** | 1.350*** | 1.372*** |
| | (0.041) | (0.037) | (0.036) |
| In House | | 0.004 | -0.036 |
| | | (0.036) | (0.039) |
| N. Potential Entrants | | | -1.25*** |
| sq. N. Potential Entrants | | | .05*** |
| N | 742 | 742 | 742 |

*Notes*: Top panel. Column 1 reports model estimates in column 6 of table 6 for comparison. In column 2, I introduce the in-house control and in column 3 the augmented model with a further stage controlling for the probability of each winner entering the competition. Among the other controls, Zone 2 is defined between 2100-3000 GG and Zone 3 above 3000 GG. The model standard errors are block bootstrapped and clustered at plant level. The capital quality proxy and the interaction term with the PPP dummy have an inverted sign such that increasing values correspond to higher levels of quality. Bottom panel. The probit model regress an entry dummy on project characteristics, tender characteristics and a suitable 2nd degree polynomia in the number of potential entrants. * Significant at the 10 percent level; ** significant at the 5 percent level; *** significant at the 1 percent level.

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# Appendices

## Appendix A

Consider the following total cost minimization problem:

$$min\ P_k K + P_l L$$

$$st\ ED = exp(\underline{a} + \delta a + \kappa e) \cdot K^{\alpha_k} \cdot L^{\alpha_l}$$

the associated cost function[23] for a DH firm operator obtained through duality is:

$$B \cdot \exp\left(-\delta a - \kappa e\right)\left(\frac{P_k^{\frac{\alpha_k}{\theta}} \cdot P_l^{\frac{\alpha_l}{\theta}}}{\theta}\right) \tag{12}$$

where $\theta = \alpha_k + \alpha_l + \alpha_{et}$ and $B = \frac{\theta \cdot ED^{\frac{1}{\theta}}}{(\alpha_k^{\alpha_k} \alpha_l^{\alpha_l})^{\frac{1}{\theta}}} \cdot \exp\left(\frac{\underline{a}}{\theta}\right)$, and $P_J$ are input prices with $j = k,\ l$. The total cost is a function of the effort, $e$, and the quality design investment, $a$, which reduce the needs of each input to produce the same level of output. The operator's cost is affected by the technological externality, $\delta$, such that the effect of the quality design investment, $a$, on cost is $\delta$. A unit increase in operational effort, $e$, induces a reduction in cost equal to the parameter $\kappa$. I am assuming that the cost of implementing the quality design investment $a$ is an exponential function, $exp(a-1)$. The operator could exert the effort $e$ in order to reduce the "input" inefficiency of her own cost $C$, whose implementing cost is the exponential function $exp(e-1)$.

Under traditional procurement, the optimal effort, $\underline{e}$, is equal to the following expression:

$$\underline{e} = \frac{\theta}{\kappa + \theta}\left[\ln B_O + \ln\left(\frac{P_k^{\frac{\alpha_k}{\theta}} \cdot P_l^{\frac{\alpha_l}{\theta}}}{\theta}\right) + \ln \kappa\right]$$

[23] Using a Cobb-Douglas cost function along with an explicit exponential expression for TFP obviously departs from generality, but satisfies my goal of showing the transmission mechanism in a simple closed form.

where $\theta = \alpha_k + \alpha_l$ and $B_O = \frac{\theta \cdot ED^{\frac{1}{\theta}}}{(\alpha_k^{\alpha_k}\alpha_l^{\alpha_l})^{\frac{1}{\theta}}} \cdot \exp\left(\frac{a}{\theta}\right)$.

Since under unbundling the optimal quality investment in design is $a^i = 0$, the operator's objective function would be:

$$\underset{e \geq 0}{max} - \left[B_O \cdot \exp\left(-\frac{\kappa e}{\theta}\right) \cdot (P_k^{\frac{\alpha_k}{\theta}} \cdot P_l^{\frac{\alpha_l}{\theta}})\right] - [\exp(e) - 1]$$

where $B_O = \frac{\theta \cdot ED^{\frac{1}{\theta}}}{(\alpha_k^{\alpha_k}\alpha_l^{\alpha_l})^{\frac{1}{\theta}}} \cdot \exp\left(\frac{a}{\theta}\right)$. Optimizing behavior implies the following first-order condition and optimal effort level $\underline{e}^*$:

$$\kappa \cdot B_O \cdot exp\left(-\frac{\kappa e}{\theta}\right) \cdot \frac{P_k^{\frac{\alpha_k}{\theta}} \cdot P_l^{\frac{\alpha_l}{\theta}}}{\theta} = exp(e) \Rightarrow$$

$$\ln B_O + \ln\left(\frac{P_k^{\frac{\alpha_k}{\theta}} \cdot P_l^{\frac{\alpha_l}{\theta}}}{\theta}\right) + \ln \kappa = e + \frac{\kappa}{\theta} e \Rightarrow$$

$$\underline{e} = \frac{\theta}{\kappa + \theta}\left[\ln B_O + \ln\left(\frac{P_k^{\frac{\alpha_k}{\theta}} \cdot P_l^{\frac{\alpha_l}{\theta}}}{\theta}\right) + \ln \kappa\right]$$

where in the second step, I applied logs to both sides.

In a PPP arrangement a public authority offers to the builder and operator, jointly in a consortium, a unique contract. The technological externality, $\delta$, directly affects the cost of the operator, since the operator enforces the builder to implement the quality investment, $a$.

Under bundling, the optimal effort, $e^{PPP}$, and the optimal quality design, $a^{PPP}$, are equal to

$$e^{PPP} = \frac{\theta}{\kappa+\delta+\theta}\left[\ln B_C + \ln\left(\frac{P_k^{\frac{\alpha_k}{\theta}} \cdot P_l^{\frac{\alpha_l}{\theta}}}{\theta}\right) - \frac{\delta}{\theta}\ln\delta + \frac{(\delta+\theta)}{\theta}\ln\kappa\right]$$

$$a^{PPP}, = \frac{\theta}{\kappa+\delta+\theta}\left[\ln B_C + \ln\left(\frac{P_k^{\frac{\alpha_k}{\theta}} \cdot P_l^{\frac{\alpha_l}{\theta}}}{\theta}\right) + \frac{\theta+\kappa}{\theta}\ln\delta - \frac{\kappa}{\theta}\ln\kappa\right]$$

where $\theta = \alpha_k + \alpha_l$ and $B_C = \frac{\theta \cdot ED^{\frac{1}{\theta}}}{(\alpha_k^{\alpha_k}\alpha_l^{\alpha_l})^{\frac{1}{\theta}}} \cdot \exp\left(\frac{a}{\theta}\right)$.

The consortium solves the following optimization problem:

$$\max_{a,\, e} \; -\left[B_C \cdot exp\left(\frac{-\delta a - \kappa e}{\theta}\right) \cdot (P_k^{\frac{\alpha_k}{\theta}} \cdot P_l^{\frac{\alpha_l}{\theta}})\right] - [exp(a) - 1] - [exp(e) - 1]$$

$$s.t.\, e \geq 0$$

where $B_C = \frac{\theta ED^{\frac{1}{\theta}}}{(\alpha_k^{\alpha_k}\alpha_l^{\alpha_l})^{\frac{1}{\theta}}} \cdot \exp\left(\frac{a}{\theta}\right)$. Optimizing behavior implies the following first order conditions:

$$FOC\, wrt\, a: \quad exp(a) = B_C \cdot (P_k^{\frac{\alpha_k}{\theta}} \cdot P_l^{\frac{\alpha_l}{\theta}}) \cdot \left(\frac{\delta}{\theta}\right) \cdot exp\left(\frac{-\delta a - \kappa e}{\theta}\right) \Rightarrow$$

$$\Rightarrow \frac{a(\delta+\theta)}{\theta} = -\frac{\kappa e}{\theta} + \ln B_C + \ln\left(\frac{P_k^{\frac{\alpha_k}{\theta}} \cdot P_l^{\frac{\alpha_l}{\theta}}}{\theta}\right) + \ln\delta \Rightarrow$$

$$\Rightarrow a = \frac{\theta}{\delta+\theta}\left[\ln B_C + \ln\delta + \ln\left(\frac{P_k^{\frac{\alpha_k}{\theta}} \cdot P_l^{\frac{\alpha_l}{\theta}}}{\theta}\right) - \frac{\kappa e}{\theta}\right]$$

$$FOC\, wrt\, e: \quad exp(e) = B_C \cdot (P_k^{\frac{\alpha_k}{\theta}} \cdot P_l^{\frac{\alpha_l}{\theta}}) \cdot \left(\frac{\kappa}{\theta}\right) \cdot exp\left(\frac{-\delta a - \kappa e}{\theta}\right) \Rightarrow$$

$$\Rightarrow \frac{e(\kappa+\theta)}{\theta} = -\frac{\delta a}{\theta} + \ln B_C + \ln\left(\frac{P_k^{\frac{\alpha_k}{\theta}} \cdot P_l^{\frac{\alpha_l}{\theta}}}{\theta}\right) + \ln\kappa \Rightarrow$$

$$\Rightarrow e = \frac{\theta}{\kappa+\theta}\left[\ln B_C + \ln\left(\frac{P_k^{\frac{\alpha_k}{\theta}} \cdot P_l^{\frac{\alpha_l}{\theta}}}{\theta}\right) - \frac{\delta a}{\theta} + \ln\kappa\right]$$

where in the second line of each FOC, I applied logs to both sides.

Substituting $a$ into $e$

$$e = \frac{\theta}{\kappa+\theta}\left\{\ln\kappa + \frac{\theta}{\delta+\theta}\left[\ln B_C + \ln\left(\frac{P_k^{\frac{\alpha_k}{\theta}} \cdot P_l^{\frac{\alpha_l}{\theta}}}{\theta}\right)\right] - \frac{\delta\ln\delta}{\delta+\theta} + \frac{\kappa e}{\theta}\frac{\delta}{\delta+\theta}\right\} \Rightarrow$$

$$e - \frac{\delta\kappa}{\delta+\theta}\frac{e}{\kappa+\theta} = \frac{\theta}{\kappa+\theta}\left\{\frac{\theta}{\delta+\theta}\left[\ln B_C + \ln\left(\frac{P_k^{\frac{\alpha_k}{\theta}} \cdot P_l^{\frac{\alpha_l}{\theta}}}{\theta}\right)\right] - \frac{\delta\ln\delta}{\delta+\theta} + \ln\kappa\right\} \Rightarrow$$

$$\frac{(\delta+\theta)(\kappa+\theta)e - \delta\kappa e}{\theta} = \theta\left[\ln B_C + \ln\left(\frac{P_k^{\frac{\alpha_k}{\theta}} \cdot P_l^{\frac{\alpha_l}{\theta}}}{\theta}\right)\right] - \delta\ln\delta + (\delta+\theta)\ln\kappa \Rightarrow$$

$$\frac{[(\kappa+\delta)\theta+\theta^2]}{\theta}e = \theta\left[\ln B_C + \ln\left(\frac{P_k^{\frac{\alpha_k}{\theta}} \cdot P_l^{\frac{\alpha_l}{\theta}}}{\theta}\right)\right] - \delta\ln\delta + (\delta+\theta)\ln\kappa \Rightarrow$$

$$(\kappa+\delta+\theta)e = \theta\left[\ln B_C + \ln\left(\frac{P_k^{\frac{\alpha_k}{\theta}} \cdot P_l^{\frac{\alpha_l}{\theta}}}{\theta}\right)\right] - \delta\ln\delta + (\delta+\theta)\ln\kappa \Rightarrow$$

$$e^{PPP} = \frac{\theta}{\kappa+\delta+\theta}\left[\ln B_C + \ln\left(\frac{P_k^{\frac{\alpha_k}{\theta}} \cdot P_l^{\frac{\alpha_l}{\theta}}}{\theta}\right) - \frac{\delta}{\theta}\ln\delta + \frac{(\delta+\theta)}{\theta}\ln\kappa\right]$$

substituting $e^{PPP}$ into $a$

$$a^{PPP} = \frac{\theta}{\delta+\theta}\left\{\frac{\delta+\theta}{\kappa+\delta+\theta}\left[\ln B_C + \ln\left(\frac{P_k^{\frac{\alpha_k}{\theta}} \cdot P_l^{\frac{\alpha_l}{\theta}}}{\theta}\right)\right] + \frac{(\delta+\theta)(\theta+\kappa)}{(\kappa+\delta+\theta)\theta}\ln\delta - \frac{\kappa(\delta+\theta)}{(\kappa+\delta+\theta)\theta}\ln\kappa\right\} \Rightarrow$$

$$a^{PPP} = \frac{\theta}{\kappa+\delta+\theta}\left[\ln B_C + \ln\left(\frac{P_k^{\frac{\alpha_k}{\theta}} \cdot P_l^{\frac{\alpha_l}{\theta}}}{\theta}\right)\right] + \frac{\theta+\kappa}{\kappa+\delta+\theta}\ln\delta - \frac{\kappa}{\kappa+\delta+\theta}\ln\kappa \Rightarrow$$

$$a^{PPP} = \frac{\theta}{\kappa+\delta+\theta}\left[\ln B_C + \ln\left(\frac{P_k^{\frac{\alpha_k}{\theta}} \cdot P_l^{\frac{\alpha_l}{\theta}}}{\theta}\right) + \frac{\theta+\kappa}{\theta}\ln\delta - \frac{\kappa}{\theta}\ln\kappa\right]$$

under bundling, TFP is an increasing function of the externality effect $\delta$.

Plugging the optimal effort, $e^{PPP}$ and the optimal quality design, $a^{PPP}$, into the productivity term:

$$exp\left\{\frac{\theta(\kappa+\delta)}{\kappa+\delta+\theta}\left[\ln B_C + \ln\left(\frac{P_k^{\frac{\alpha_k}{\theta}} \cdot P_l^{\frac{\alpha_l}{\theta}}}{\theta}\right) + \frac{\delta}{(\kappa+\delta)}\ln\delta + \frac{\kappa}{(\kappa+\delta)}\ln\kappa\right]\right\}$$

where if $\phi = \frac{(\kappa+\delta)(\theta)}{\kappa+\delta+\theta}$ and $\zeta = \frac{\delta}{(\kappa+\delta)}$, $\phi \to \theta$ and $\zeta \to 1$ when $\delta \to \infty$, and $exp\{\phi \cdot lg[B_C \cdot \frac{P_k^{\frac{\alpha_k}{\theta}} \cdot P_l^{\frac{\alpha_l}{\theta}}}{\theta} \cdot \zeta\delta]\} \to \infty$ at the speed $lg\delta$.

## Appendix B

In this appendix I show how intermediate material, $ET_{it}$, can be exploited as a proxy for productivity. The proof is intended to state sufficient conditions for intermediate materials demand to be a strictly increasing function of productivity $\omega_{it}$.

Input markets are assumed to be competitive. Conversely, the output market is a natural monopoly. DH firms exert their market power up to a cap prize $\bar{P}$, such that switching to the outside technology (autonomous boilers) becomes convenient for customers. The DH firm's ability to exploit its monopoly power depends on the level of the switching costs, which create lock-in effects for customers. A recent study by the Italian Competition Authority (ICA) suggests the occurrence of lock-in effect in the Italian DH sector to be rare.

Capital is considered quasi-fixed, so optimal investment stems from a policy function which is the solution to a dynamic optimization problem. Practically, this means that capital is not a variable to optimize at time $t$ in the firm's static problem.

Assume that a DH firm has a production technology $F(K,\, L,\, ET,\, \Omega) : R^4_+ \rightarrow R_+$ twice continuously differentiable in labor, $L$, and intermediate materials input, $ET$; the partial derivatives $\frac{\partial F}{\partial L \partial \Omega^A}$, $\frac{\partial F}{\partial ET \partial \Omega^A}$ and $\frac{\partial F}{\partial ET \partial L}$ exist for all values of $(K,\, L,\, ET,\, \Omega,\,) \in R^4_+$; the input markets are competitive, but the output is not; either investment at time $t$ does not respond to productivity at time $t$, or capital at time $t$ is not a function of investment at time, $t$; the productivity shock, $\Omega = \Omega^{AFTER} = \Omega^A$, is observed before the choice of labor and intermediate material is made. Under these assumptions, if the following expression

$$\frac{\partial F}{\partial ET \partial L}\frac{\partial F}{\partial ET \partial \Omega^A} - \frac{\partial F}{\partial ET \partial \Omega^A}\frac{\partial F}{\partial L^2} + \frac{1}{\eta F}\left(\frac{\partial F}{\partial ET}\frac{\partial F}{\partial \Omega^A}\frac{\partial F}{\partial L^2} - \frac{\partial F}{\partial ET \partial \Omega^A}\frac{\partial^2 F}{\partial L} - \frac{\partial F}{\partial L \partial ET}\frac{\partial F}{\partial L}\frac{\partial F}{\partial \Omega^A} - \frac{\partial F}{\partial L}\frac{\partial F}{\partial ET}\frac{\partial F}{\partial L \Omega^A}\right) > 0$$

holds everywhere, then the intermediate input demand function,$ET(\Omega;\, P_{ET}\, P_L\, P_K\; k)$, is strictly increasing in $\Omega$.

After the realization of $\Omega^A$, a profit-maximizing DH firm solves the following optimization problem with respect to its free variable input $L$ and $ET$:

$$\max_{ET,\, L,} P(ED) \cdot ED - P_{ET} \cdot ET - P_K \cdot K - P_L \cdot L$$

$$s.t.\;\; ED = F(K,\, ET,\, L,\, \Omega^A)$$

where $P(ED)$ is the inverse demand function and $P_j$ the respective prices of the inputs. First-order conditions are:

$$P(F)\frac{dF}{dj} + F\frac{dP}{dF}\frac{dF}{dj} = P_j \; with \; j = ET,\, L$$

multiplying and dividing by $P$ the second member of the lhs and substituting $1/\eta = -\frac{F}{dF}\frac{dP}{P}$.

$$P(F)\frac{dF}{dj} - \frac{dF}{dj}\frac{P}{\eta} = P_j \Rightarrow P(F)\frac{dF}{dj}(1 - \frac{1}{\eta}) = P_j \Rightarrow$$

$$\Rightarrow P(F)\frac{dF}{dj} = \frac{P_j}{(1-\frac{1}{\eta})} \; with \; j = ET, \, L$$

both $P(F(K, \, ET, \, L, \, \Omega^A))$ and $\frac{dF(K, \, ET, \, L, \, \Omega^A)}{dj}$ are functions of productivity $\Omega^A$. Taking derivatives of both sides with respect to $\Omega^A$, we obtain:

$$\frac{dP(F)}{dF}\frac{dF}{d\Omega^A}\frac{dF}{dj} + P(F)\frac{dF}{djd\Omega^A} = 0 \; with \; j = ET, \, L$$

divide equation by $P$ and total differentiate $dF(K, \, ET, \, L, \, \Omega^A)$ and $\frac{dF(K, \, ET, \, L, \, \Omega^A)}{dj}$ :

$$\frac{dP(F)}{dF}\frac{1}{P}\frac{\partial F}{\partial j}\left(\frac{\partial F}{\partial ET}\frac{\partial ET}{\partial \Omega^A} + \frac{\partial F}{\partial L}\frac{\partial L}{\partial \Omega^A} + \frac{\partial F}{\partial \Omega^A}\right) + \left(\frac{\partial F}{\partial j \partial ET}\frac{\partial ET}{\partial \Omega^A} + \frac{\partial F}{\partial j \partial L}\frac{\partial L}{\partial \Omega^A} + \frac{\partial F}{\partial j \partial \Omega^A}\right) = 0 \; with \; j = ET, \, L$$

which can be equivalently rewritten as:

$$\left(\frac{\partial F}{\partial j \partial ET}\frac{\partial ET}{\partial \Omega^A} + \frac{\partial F}{\partial j \partial L}\frac{\partial L}{\partial \Omega^A} + \frac{\partial F}{\partial j \partial \Omega^A}\right) - \frac{1}{\eta F}\frac{\partial F}{\partial j}\left(\frac{\partial F}{\partial ET}\frac{\partial ET}{\partial \Omega^A} + \frac{\partial F}{\partial L}\frac{\partial L}{\partial \Omega^A} + \frac{\partial F}{\partial \Omega^A}\right) = 0 \; with \; j = ET, \, L$$

Which can be restated in matrix form as:

$$\begin{pmatrix} \frac{\partial F}{\partial ET^2} - \frac{1}{\eta F}(\frac{\partial F}{\partial ET})^2 & \frac{\partial F}{\partial ET \partial L} - \frac{1}{\eta F}\frac{\partial F}{\partial L}\frac{\partial F}{\partial ET} \\ \frac{\partial F}{\partial L \partial ET} - \frac{1}{\eta F}\frac{\partial F}{\partial L}\frac{\partial F}{\partial ET} & \frac{\partial F}{\partial L^2} - \frac{1}{\eta F}(\frac{\partial F}{\partial L})^2 \end{pmatrix} \begin{pmatrix} \frac{\partial ET}{\partial \Omega^A} \\ \frac{\partial L}{\partial \Omega^A} \end{pmatrix} = \begin{pmatrix} \frac{1}{\eta F}\frac{\partial F}{\partial ET}\frac{\partial F}{\partial \Omega^A} - \frac{\partial F}{\partial ET \partial \Omega^A} \\ \frac{1}{\eta F}\frac{\partial F}{\partial L}\frac{\partial F}{\partial \Omega^A} - \frac{\partial F}{\partial L \partial \Omega^A} \end{pmatrix}$$

Applying Cramer's rule:

$$\frac{\partial ET}{\partial \Omega^A} = \frac{\begin{Vmatrix} \frac{1}{\eta F}\frac{\partial F}{\partial ET}\frac{\partial F}{\partial \Omega^A} - \frac{\partial F}{\partial ET \partial \Omega^A} & \frac{\partial F}{\partial ET \partial L} - \frac{1}{\eta F}\frac{\partial F}{\partial L}\frac{dF}{dET} \\ \frac{1}{\eta F}\frac{\partial F}{\partial L}\frac{\partial F}{\partial \Omega^A} - \frac{\partial F}{\partial L \partial \Omega^A} & \frac{\partial F}{\partial L^2} - \frac{1}{\eta F}(\frac{\partial F}{\partial L})^2 \end{Vmatrix}}{\begin{Vmatrix} \frac{\partial F}{\partial ET^2} - \frac{1}{\eta F}(\frac{\partial F}{\partial ET})^2 & \frac{\partial F}{\partial ET \partial L} - \frac{1}{\eta F}\frac{\partial F}{\partial L}\frac{dF}{dET} \\ \frac{\partial F}{\partial L \partial ET} - \frac{1}{\eta F}\frac{\partial F}{\partial L}\frac{\partial F}{\partial ET} & \frac{\partial F}{\partial L^2} - \frac{1}{\eta F}(\frac{\partial F}{\partial L})^2 \end{Vmatrix}}$$

Note that the denominator is the Hessian matrix. The stated assumptions imply that this matrix is negative semidefinite, i.e. the determinant of the Hessian is positive. Consequently, a profit-maximizing DH firm has intermediate input demand such that the following is verified:

$$sign\left(\frac{\partial ET}{\partial \Omega^A}\right) = sign\left\| \begin{matrix} \frac{1}{\eta F}\frac{\partial F}{\partial ET}\frac{\partial F}{\partial \Omega^A} - \frac{\partial F}{\partial ET \partial \Omega^A} & \frac{\partial F}{\partial ET \partial L} - \frac{1}{\eta F}\frac{\partial F}{\partial L}\frac{\partial F}{\partial ET} \\ \frac{1}{\eta F}\frac{\partial F}{\partial L}\frac{\partial F}{\partial \Omega^A} - \frac{\partial F}{\partial L \partial \Omega^A} & \frac{\partial F}{\partial L^2} - \frac{1}{\eta F}(\frac{\partial F}{\partial L})^2 \end{matrix} \right\|$$

Under mild regularity conditions on $F(\cdot)$ such that the Fundamental Theorem of Calculus holds for $ET(\cdot)$, the following is true:

$$ET(\omega_2;\, P_{ET}\, P_L\, P_K\, K) - ET(\omega_1;\, P_{ET}\, P_L\, P_K\, K) = \int_{\omega_1}^{\omega_2} \frac{\partial ET(\omega;\, P_{ET}\, P_L\, P_K\, K)}{\partial \omega} P(d\omega)$$

where $\omega_2 > \omega_1$. If the following condition holds everywhere:

$$\frac{\partial F}{\partial ET \partial L}\frac{\partial F}{\partial ET \partial \Omega^A} - \frac{\partial F}{\partial ET \partial \Omega^A}\frac{\partial F}{\partial L^2} + \frac{1}{\eta F}\left(\frac{\partial F}{\partial ET}\frac{\partial F}{\partial \Omega^A}\frac{\partial F}{\partial L^2} - \frac{\partial F}{\partial ET \partial \Omega^A}\frac{\partial^2 F}{\partial L} - \frac{\partial F}{\partial L \partial ET}\frac{\partial F}{\partial L}\frac{\partial F}{\partial \Omega^A} - \frac{\partial F}{\partial L}\frac{\partial F}{\partial ET}\frac{\partial F}{\partial L \partial \Omega^A}\right) > 0$$

it follows that:

$$\int_{\omega_1}^{\omega_2} \frac{\partial et(\omega;\, P_{ET}\, P_L\, P_K\, K)}{\partial \omega} P(d\omega) > \int_{\omega_1}^{\omega_2} 0 P(d\omega) = 0$$

finally, we obtain:

$$ET(\omega_2;\, P_{ET}\, P_L\, P_K\, K) > ET(\omega_1;\, P_{ET}\, P_L\, P_K\, K)$$

# Appendix C

The complete Taylor expansion of $\omega(a,\, \text{e};\, PPP)$ in equation (4):

$$\omega(a,\, \text{e};\, PPP) \simeq \omega^{TP} + \frac{\partial \omega^{TP}}{\partial a}\cdot a + \frac{\partial \omega^{TP}}{\partial e}\cdot e +$$

$$-\omega^{TP}\cdot PPP - \frac{\partial \omega^{TP}}{\partial a}(a \cdot PPP) - \frac{\partial \omega^{TP}}{\partial e_{it}}(e \cdot PPP)$$

$$+\omega^{PPP}\cdot PPP + \frac{\partial \omega^{PPP}}{\partial a}(a \cdot PPP) + \frac{\partial \omega^{PPP}}{\partial e}(e \cdot PPP)$$