

On the Vibration Analysis of Coupled Transverse and Shear Piezoelectric FG Porous Beams with Higher-Order Theories

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## A feasibility study on the potential expansion of the district heating network of Turin

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### Abstract

Reduction in energy consumptions and CO<sub>2</sub> emissions and increase in the use of renewable energy sources can be reached through large scale implementation of energy efficiency measures. In urban contexts, district heating (DH) systems are expected to allow integration of waste heat and thermal renewable sources. In this work we propose a GIS-based model for the technical feasibility analysis of possible expansions of existing DH networks. The application to the City of Turin is presented as a case study.

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*Keywords:* district heating; energy efficiency measures; building; feasibility study; future expansion scenarios

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### 1. Introduction

Some of the key actions in sustainable development policies are the promotion of building retrofitting with the aim of improving the energy performance, and the development, exploitation and integration of renewable sources. Efficient heat supply systems based on renewable energy sources are an important element of energy systems that are compliant with these goals [1]. End-use energy savings and expansion of district heating are measures to make the heat supply sector more sustainable [2, 3]. Recent analyses show that a substantial reduction in fuel demands and CO<sub>2</sub> emissions as well as cost can be achieved by combining district heating expansion with end-use energy savings

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[2, 4, 5]. This work starts from an assessment of sustainable energy models at urban scale with the objective of defining possible options to be applied in Italy, taking into account the available technologies to exploit renewable energy sources in the various areas [6 - 12]. Particularly, the energy-use models for space heating consumption of buildings are investigated considering a hybrid approach with bottom-up and top-down models [13]. High-density urban contexts make district heating more convenient, due to the fact that heat distribution costs vary considerably with population density, and tend to decrease in larger agglomerations and regions with high specific heat demands [14, 15]. The following study introduces a general model which aims at evaluating the potential of expansion of existing district heating networks. An application to the Turin district heating (the largest district heating network in Italy and one of the largest in Europe) is proposed. The various technical limitations are considered in the analysis: the Po river, which is difficult to cross with the DH network, and the hills, the high density historical center, the buildings with individual heating systems, and the maximum flow rate which can be transmitted in each portion of the pipeline. With the support of a GIS tool, the main characteristics of buildings were analyzed: their volume, type of users, typology of heating systems and fuel utilized. Through the municipal technical map of Turin the volumes connected by the DH network were represented ( $59.4 \text{ Mm}^3$ ) and those potentially connectable were calculated, considering residential, public, commercial and industrial types of buildings. The latter piece of information was available for the entire city of Turin on a mesh of  $1 \text{ km} \times 1 \text{ km}$ , and an accuracy at building scale only on the central district. The model was validated using the data of energy consumptions provided by the DH company. Two future scenarios of a district heating network expansion were foreseen: a short to medium term scenario, with the possibility of connecting buildings to the existing DH network, and the long term scenario, with the possibility to install new pipelines to connect all the buildings. A fluid dynamic model of a district heating network is used in order to simulate the mass flow rates distribution for the existing and the future scenarios. The model allows evaluating the maximum velocity value that occurs in the transportation network applying the conservation equations to all the network pipelines.

## 2. Case study

Turin municipality has proposed its energy and environmental planning with the objective of protecting the environment and increasing the use of renewable energies and significantly reduce its  $\text{CO}_2$  emissions (TAPE – Turin Action Plan for Energy, 2009). The heat demand in the Turin buildings is quite large; most of it, about 55%, is covered by the existing district heating. To increase energy sustainability in such an urban context such, a crucial aspect consists in the optimization of the energy demand of different users. The complex local context of Turin has a significant influence on the planning processes and the various territorial constraints should be considered while examining possible expansions of the DH network. In addition, two conditions related to economic sustainability are imposed: buildings must have a central heating system and they must have a volume larger than a minimum value of  $2500 \text{ m}^3$ . In Turin there are about  $25 \text{ Mm}^3$  ( $20 \text{ Mm}^3$  residential and  $5 \text{ Mm}^3$  non-residential) localized in high density historical center and about  $8 \text{ Mm}^3$  ( $6.5 \text{ Mm}^3$  residential and  $1.5 \text{ Mm}^3$  non-residential) localized beyond the Po river and in the hills. Turin has about 60'000 heated buildings ( $232 \text{ Mm}^3$ ). The residential patrimony is constituted by more than 45'000 buildings, corresponding to  $164 \text{ Mm}^3$ , while the non-residential buildings are around 14'000, corresponding to  $68 \text{ Mm}^3$  (municipal technical map of Turin, 2015). The district heating is continuously evolving; in 2009 the network was serving about  $44 \text{ Mm}^3$  of buildings, while the connection of an additional  $18 \text{ Mm}^3$  was planned in 2009 and further developments of  $24 \text{ Mm}^3$  in the following years, as documented in the Turin development plan of a district heating (2009). Data supplied by the DH company show that the DH network in January 2016 was serving about  $60 \text{ Mm}^3$  through a complex network of over 500 kilometers and 5.700 heat exchange substations. About 2000 GWh/year of thermal energy are introduced in the network and over 98% of that energy is produced through cogeneration systems. The main data used to set the model are: the Turin Action Plan for Energy (2009), the Turin development plan of district heating (2009), the Municipal Technical Map of Turin (2015), the data of the census ISTAT 2011, the data about the type of buildings' heating systems (ISTAT 2011), the physical-territorial limits (Po river and hills), the historical center with the LTZ (limited traffic zone), and the existing DH network. In addition, the real consumptions available from the DH company have been used for the buildings already connected with the district heating network.

### 3. Methodology

Starting from the energy-use model at urban scale [13] for the city of Turin, the specific consumption of buildings for the different users were estimated and the DH potentials areas have been identified (Fig. 1a, Fig. 1b). The potential of a future expansion of the DH network was evaluated. Considering that in January 2016 the heated volume connected to the DH network of Turin was of 59.4 Mm<sup>3</sup> (IREN data and DIMMER project), it will be possible to connect, on the medium term, additional 81.9 Mm<sup>3</sup>. In the case of a long term scenario, more 25.3 Mm<sup>3</sup> can be connected (about 65.4 Mm<sup>3</sup> are not connectable because of the territorial constrains).

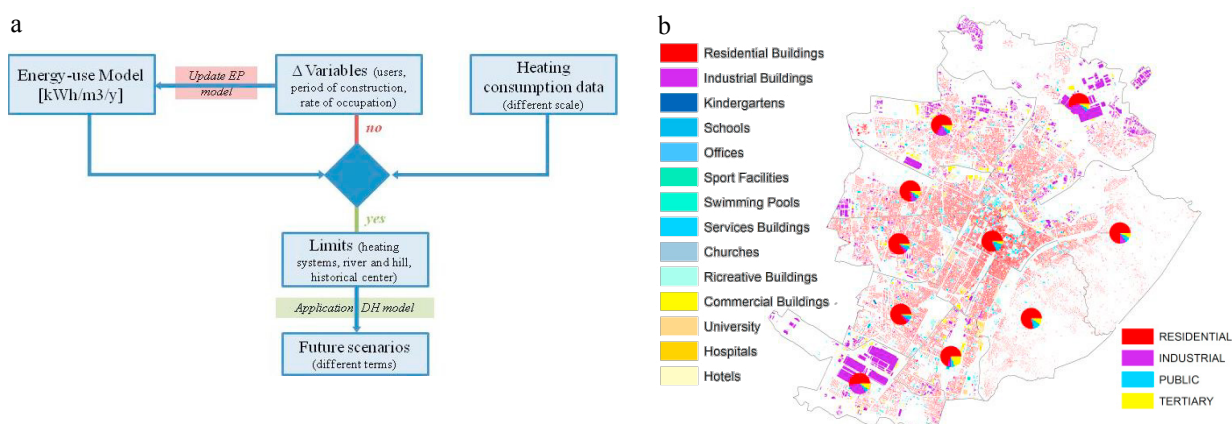


Fig. 1. (a) Methodological flowchart of the procedure; (b) The different types of the analysed buildings in the 10 districts of Turin (residential, industrial, public and tertiary buildings).

Turin consumption data [MWh] and volumes served [m<sup>3</sup>] are provided by the district heating company, IREN. Data cover the city through 59 meshes of the size of 1 km x 1 km. At building scale, for a specific area of Turin (n.1193 mesh - Duca of Abruzzi area), the volumetric data of 201 substations are available (DIMMER project). The volumetric portion connected to the network (state of fact), calculated by the model (47.07%) was compared with the data of substations (46.01%) for a mesh of 1 km x 1 km (201 substations, for 149 of which full data are available) (Fig. 2a). With a GIS tool, the centroids (sub-networks) and the DH network were georeferenced, for each mesh of 1 km<sup>2</sup> centroids have been associated, localized inside the meshes (a total of 182 centroids, 177 of which are located within the meshes of 1 km<sup>2</sup>). With a fluid dynamic model of the district heating network the feasibility was assessed (Fig. 2a). The constraints for a future expansion of the district heating network (Fig. 2b) were evaluated: the presence of individual heating systems (28.4%), the territorial limits given by the Po river and the hills, and the high density historical old town in the centre of Turin. From the analysis of the current state, the areas potentially connectable to the existing network have been identified and the bound areas have been excluded. These are the non connectable buildings, because of a volume smaller than 2500 m<sup>3</sup> or the presence of an individual and autonomous heating system. The connected and the potential portions (expressed in % and m<sup>3</sup>) have been calculated. Additional limitations to the connection of buildings are due to the diameter of the existing pipeline. In fact, there is a maximum limit for the velocity of water inside the pipeline, which depends on the diameter. For the transport network, i.e. the portion of pipeline connecting the thermal plants to the subnetworks, this limit is about 4-4.5 m/s. In order to analyze the new connections that are allowed, a set of tests has been conducted. For each subnetwork, the fraction of volume available for additional connections was evaluated, as discussed in the previous section. The possibility of connecting different fractions of the connectable volume is also studied. In particular, fractions from 10% to 60% of the connectable volumes are considered for each district of the network. In order to evaluate the maximum value of the water velocity inside the pipelines, a DH network model is used. A one-dimensional fluid-dynamic model, based on mass and momentum conservation equations has been applied to the entire transport network. A graph approach has been used to describe the network topology. More details about the model are available in [16]. To provide water to the various districts, a pumping system is installed in all the plants and a

certain number of booster pumping stations are located along the network. The booster pumping stations on the supply network are 8, both the pumping stations 1 and 2 include two pumps each, pumping station 3 includes a single pump, while pumping station 5 includes 3 pumps. Pumping station 4 is the only pump installed in the return line of the network. The power of the pumps installed in the plants is a consequence of the mass flow rate that the plants produce, related to the thermal request of the entire network, while the power of the booster pumping station depends on the regulation approach. For the present work, a certain number of pumping power sets are considered and the best value in terms of lower water velocity is considered. In particular, 300 sets of pumping power are randomly selected for each booster station. A power interval has been selected for each pumping station as discussed in [16]. This is done in order to exclude, for each pumping station, the values of power that, with a high probability, leads to the violation of the maximum pressure limit along the network, which is 17 bar.

#### 4. Results and discussion

The quota of total volumes connected to the existing DH network has been revised in order to analyze abnormal data. The maximum volume served for each mesh of 1 km<sup>2</sup> was selected. The total connected volume was calculated by the summation of the maximum volume connected, equal to 59.410.159 m<sup>3</sup>. Considering 59 Mm<sup>3</sup> connected to the DH network, the total potential expansion (46.0%) has been calculated. The potential expansion considering that the constrained areas amounted to 41.3% (4.7% constraints). In the second phase of the work, an evaluation of the short-medium term and long term interventions have been made and the percentage of expansion has been calculated (Fig. 3a). So, starting from 59 Mm<sup>3</sup> and considering the constrained areas (Fig. 2b), two scenarios of expansion have been hypothesized. The short-medium term has a lower expansion costs and considers the buildings connectable to the existing network (1). In the long term scenario, the potentially connectable volumes are considered and the investment costs are higher than in the first scenario, due to the construction of new pipelines (2). In details, the results of the future DH network expansion scenarios are the following:

(1) Potential expansion in the short-medium term: total volume 178.148.971 m<sup>3</sup> (118.738.812 m<sup>3</sup> considering DH); connectable volume (considering quota served, heating systems and constraints): 81.882.333 m<sup>3</sup> (56.286.113 m<sup>3</sup> residential - 25.596.221 m<sup>3</sup> non-residential); no connectable volume: 36.856.479 m<sup>3</sup>.

(2) Potential expansion in the long term: total volume 232.041.148 m<sup>3</sup> (172.630.989 m<sup>3</sup> considering DH); connectable volume (considering quota served, heating systems and constraints): 107.230.527 m<sup>3</sup> (68.630.912 m<sup>3</sup> residential - 38.599.614 m<sup>3</sup> non-residential); no connectable volume: 65.400.462 m<sup>3</sup>.

For the meshes represented in Fig. 3b, the network feasibility was evaluated. The volumes and the percentage of connectable quota to existing network were calculated, considering different types of users: residential sector, public sector, service sector and industrial sector.

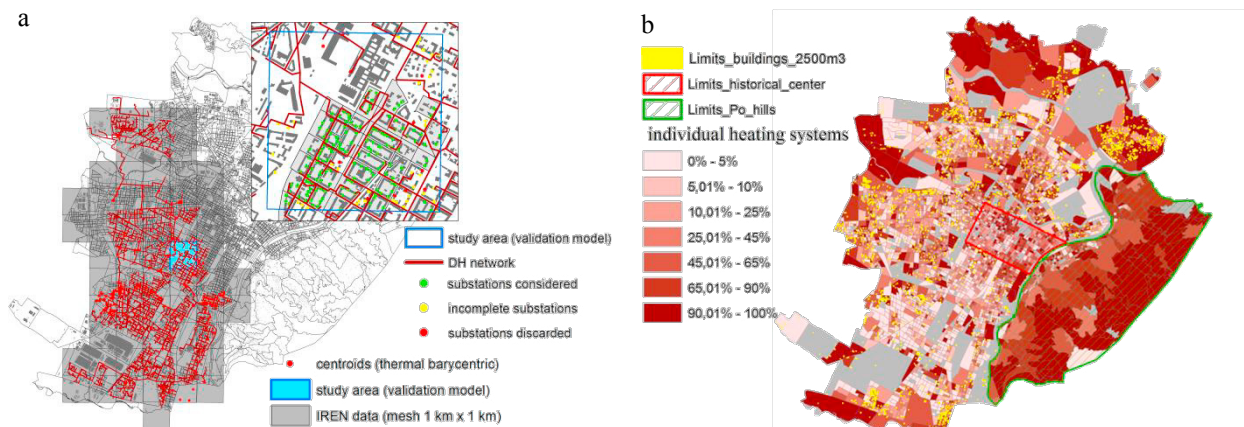


Fig. 2. (a) Location of a district heating network and available consumption data, at the top right the zoom of n.1193 mesh: identification of substations and census sections used for the validation of the model; (b) The data about individual heating systems and the limits on DH network expansion due to the rivers, the hill (in green), the historical town the centre (in red) and the buildings with a volume < 2500 m<sup>3</sup> (in yellow).

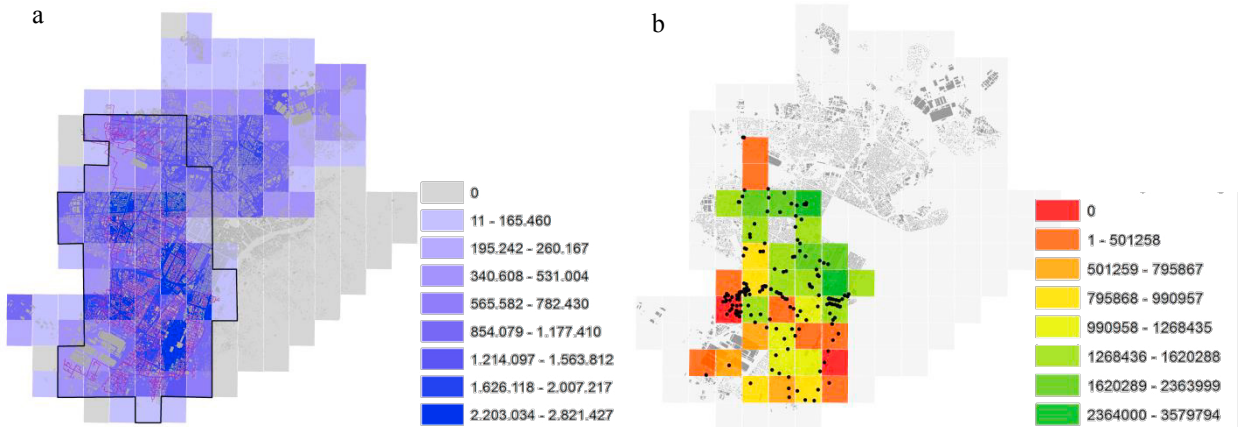


Fig. 3. (a) The maximum expansion [m<sup>3</sup>] of a DH network in the city of Turin starting from the existing network (in purple) and the expansion (m<sup>3</sup>) of a DH in the short to medium term marked with black outline; (b) Total potential expansion of a DH network [m<sup>3</sup>] with application the fluid-dynamic model, the black points are the centroids.

The fluid-dynamic model has been applied to the transport network in order to simulate the design scenario. In particular, 300 tests have been conducted and the maximum velocity  $v_{MAX}$  is evaluated for each test. The case characterized by the minimum value of  $v_{MAX}$  is considered as the best control strategy. Therefore, a value of  $v_{MAX\_BEST}$ , the  $v_{MAX}$  obtained with the best regulation among the tested, is evaluated for each fraction of connectable users that have been considered.

In Fig. 4a the percentage increase of the  $v_{MAX\_BEST}$  for the scenario corresponding with the current connected volume is reported. It is shown that, with an addition of 10% of the connectable users, the maximum velocity remains unchanged. This occurs because this connectable volume is located in areas which can be reached through pipes where velocity is below the limit. The addition of 20% leads to a small increase in  $v_{MAX\_BEST}$ , below 2%. When more than 20% of the connectable users are considered, the value of maximum velocity changes considerably, from 7% when the addition is the 30%, until 30%, when the addition is 60%.

In Fig. 4b the  $v_{MAX\_BEST}$  is presented for all the considered cases. The values obtained are situated between 4.17 m/s and 5.34 m/s. Considering 4.5 m/s as a reasonable limit, the addition of about 30% of the connectable users of each district cannot be considered in the current conditions. Current conditions refer to the network with the current pipeline configuration (and with the consequent limitation due to the maximum pipes diameter), the approach and assumptions previously defined (i.e. adding a precise fraction of the connectable users for each district), and no distinction between the different types of buildings. This limitation can be also overcome through installation of distributed storage units [18] or the implementation of peak shaving strategies [19,20].

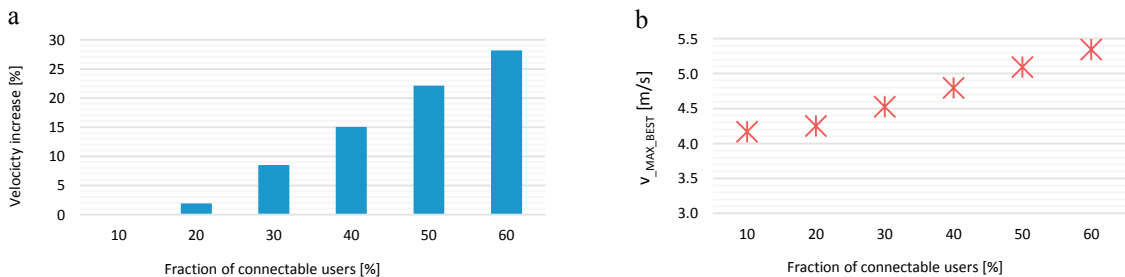


Fig. 4. Maximum velocity in the best regulation test for each connectable fraction considered. (a) Percentage velocity increase; (b) Maximum velocity.

## 5. Conclusion

With a district heating network, substantial environmental benefits can be reached in line with a sustainable urban development. The analysis of the DH network in the City of Turin shows a positive technical potential of expansion. The expansion of the network analysis implies various actions: 1) assessment of the cost/benefit considering short-term expansion using the existing network and long-term expansion with new pipelines (higher investment costs); 2) evaluation cost/benefit considering the air quality data and the social costs; 3) evaluation of environmental policies of the expansion on DH, considering a gradual retrofit of buildings (beginning from public buildings). For testing the potential for new connections with the current network design and the consequent limitations due to pipeline diameters, a fluid-dynamic network model has been applied to the Turin transport network. The analysis is performed considering different fractions of all the connectable users, for each district of the network. Results show that the addition of up to 20% of the connectable users can be performed without changes in the pipeline. These results can be enhanced in the future by considering different criteria, such as the connection of non-homogeneous fractions of users in the different districts of the network or the installation of distributed thermal storage units.

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