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Energy monitoring of manufacturing plants: a real case application

Nicla Frigerio[a,], Andrea Matta[a], Marco Rasella[b]

[a]*Mechanical Engineering Department, Politecnico di Milano, via G. la Masa 1, MIlano, Italy*
[b]*Advanced Technology Valve SPA, Via Ombriano 2, Colico, Italy*

* Corresponding author. Tel.: +39-02-2399-8559 ; fax: +39-02-2399-8530. *E-mail address:* nicla.frigerio@polimi.it

Abstract

Industries are increasingly demanded to became more green and, at the same time, the process of becoming more connected and automated enabled the measurement of actual energy flows. Indeed, the use of power meters is increased and energy related KPIs are becoming more relevant. High industrial interest is pointed to monitor the energy consumption, to automatically assess energy efficiency, and to identify potentialities for improvement. Nevertheless, monitoring systems are often limited to a certain area or resource and the plant-level vision is not common. Also, the attention is often focused on a particular process, usually energy-intense. The work presents the application of an on-line energy monitoring system to the analysis of the overall plant consumption of a real factory in Italy. The factory produces a full range of valves and actuators for the most critical applications of Oil & Gas industry, and faces with high energy consumption due to the nature of the involved processes (i.e., welding, machining, painting, and high-pressure testing). Monitored data are used to understand plant hot-spots in terms of energy consumption and to create a map of the most (or least) efficient areas of the plant so that specific measures can be implemented to reduce carbon footprint. Indications for a data-driven monitoring system to enable the identification of unexpected and unwanted behaviors are defined.

Keywords: Sustainability; Manufacturing automation; Energy monitoring; Sustainable Production Automation

1. Introduction

In the last decade, two fundamental aspects have gain impressive importance in manufacturing: energy efficiency and digitalization. Indeed, industries are increasingly demanded to became more green and, at the same time, the process of becoming more connected and automated enabled the monitoring of processes and of actual energy flows.

Despite the topic of industrial smart energy metering appeared around ten years ago (e.g. [1, 2, 3, 4, 7]), the awareness of energy efficient manufacturing systems has not been considered with the appropriate attentiveness until the last years. Thus, energy monitoring remains a key challenge in modern industry and monitoring of manufacturing processes represents a driver for development of sustainable manufacturing automation.

Energy-related key performance indicators (KPIs) are becoming more relevant for competitiveness. Sets of energy-related KPIs are suggested in the literature, as example among the others [4]. Although the necessity to include energy monitoring feedback into all layers of the manufacturing management system is clear from the literature, applications are often limited to a certain area, to a certain resource, or to a certain process which is particularly energy-intense so as it exists a lack of knowledge at factory level.

Significant effort has been devoted in recent literature to create data-driven models for industrial energy savings. A recent survey on industrial data-driven energy savings can be found in [5]. The survey presents an interesting analysis on the current situation on the topic and provide guidelines. Nevertheless, the authors remark the gap among researches and industrial practice to be filled as future challenge.

Integrating energy efficiency as a key criterion in production management and the integration still poses a huge challenge for decision-makers due to a lack of knowledge about the linkage between energy efficiency and productivity. Industrial smart energy metering is key subject of recent literature, e.g., [9, 8].

In accordance with the literature, energy mapping includes four phases: (i) energy audit to reveal energy hot-spots and potential inefficiency; (ii) identify energy losses by coupling energy data with productivity variables; (iii) evaluate production-oriented energy performance indicators to highlight energy inefficiencies and to indicate improvement directions; (iv) definition of improvement strategies. Real case applications of the

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four phases are rare and developed within strict boundaries (single resources or small set of resources, e.g. [9]).

This work intends to cover the first (i) aforementioned phase of energy mapping by presenting the application of an on-line energy monitoring system to the analysis of the overall plant consumption of a manufacturing company. Analyses are executed at factory level providing a vision of the whole company so that several technologies, auxiliary systems, and a wide variety of resources are considered. Overall energy consumption and power signature of the plant are provided. A map of plant energy efficiency is created by clustering data according to the acquisition time of the day. Indications for a smart data-driven monitoring system close the work.

2. Real case description

The company under investigation supplies to the offshore industry a full range of valves and actuators that can operate at great ocean depths (deep and ultra-deep waters, up to 3.000 m). Moreover, it offers a full range of valves for hydrocarbons processing, for pipeline applications and for both the fossil power and nuclear power industries. Company headquarters and manufacturing facilities are located in Northern Italy and cover an area of 40,000 square meters.

The production site is divided in three main areas, namely buildings C2, C12 and O2, where production departments are located (Figure 1). C2 includes offices and the machining department with 21 machine tools. Given the high variability of product dimension, the departments includes machine tool of very different size. Machines work as stand alone and operators perform machine setting, cleaning, and load/unload operations. Testing department is in O2 and it is separated in two parts: new and old part. Testing is performed in cells that are equipped properly to replicate working condition of valves. Operators perform cell setting operations. Building C12 includes the canteen and the following departments: painting, welding and another testing area. Painting department is organized in painting cabins where operations are manual. Welding department is organized in 29 robotized cells according to robot load capacity. Operators perform robot cell setting operations. Each building is served by a dedicated compressed air system for a total of three systems.

The installed monitoring system includes seven instruments measuring current and voltage of electrical cabins such that the power request of the all production site is measured. The acquisition is performed each 10 minutes over the whole day and data are stored in an indexed database. The instruments are located as follows:

- Instruments N1 and N2 are located in C2;
- Instruments N3 and N4 are located in O2;
- Instruments N5, N6 and N7 are located in C12.

The acquired data allow to collect the following 14 signals allocated to the three main buildings:

Fig. 1. Overall ATV layout

1. Machining department in C2;
2. Offices in C2;
3. Compressed air system in C2;
4. General consumption of C2 (which is the sum of signals 1,2, and 3);
5. Testing department (new area) in O2;
6. Testing department (old area) in O2;
7. Compressed air system in O2;
8. General consumption of O2 (which is the sum of signals 5,6, and 7);
9. Canteen in C12;
10. Painting department in C12;
11. Testing department in C12;
12. Compressed air system in C12;
13. Welding department in C12;
14. General consumption of C12 (which is the sum of signals 9,10,11,12, and 13).

3. Data analysis

Data analyses included in the paper cover the period between June 1st 2020 and June 27th 2021 for a total of 54 weeks and 56,448 data points of each acquired signal. As exception, the data acquired in October 2020 from building C2 are not included due to an acquisition problem. The monitoring system has been recently installed, therefore, data before the pandemic outcome are not available.

3.1. Energy audit

Monthly energy consumption is in Figure 2. In terms of general consumption of the buildings, the highest share belongs to C12 (47%), followed by O2 (27%) and C2 (26%). It is noteworthy that the consumption is not balanced along the acquired time period due to the link between energy consumption and production load. Company production volumes are not balanced among months so that energy consumption is not balanced as well.

The most energy-intense department is the welding department (26%), followed by the testing department having a total of 27% including testing in O2 (new part 11% and old part 9%) and in C12 (7%), and by the machining department (20%). Also, a significant consumption is associated to the compressed air systems with a total of 15% (4% in C2, 4% in O2 and 7% in C12). Energy flows are reported in Figure 3 and the energy consumption distribution according to departments is in Figure 4.

3.2. Power signature

The power signature of the company has been analyzed into details. As an example, the general power request of O2 over week n35 is provided in Figure 5. Clearly, power request increases during the days and drops during nights and in the week-end. It can be noticed that some activities have been executed on Saturday morning as exceptional activities. Each morning is characterized by a power peak due to the starting of production activities, whereas the power decreases along the day. During nights and week-ends, the power is constant. Nevertheless, the power consumed in the night-shift and during the week-end is significant (around 50kW in Figure 5).

In order to better describe the data set, the frequency histogram of each power signal has been created. As an example, the histogram of the general power request of C2 is in Figure 6. Power distribution in Figure 6 lays on the interval [0; 465] kW and presents two separated parts. The right-hand side of the histogram represents an almost normal distribution centered on the most common power request during daily production. The left-hand side of the histogram represents the nights and, in general, the non productive periods. For energy efficient processes, the latter should be as close as possible to zero meaning that energy wastes are avoided.

The company works over two shifts for five days per week: first shift is from 6am to 2pm, and second shift is from 2:30pm to 10:30pm. Data are clustered according to the shift (night is considered as third shift) and the day of the week (namely, Monday is 1 and Sunday is 7).

$$R_{2-1} = \frac{\textit{Average power second shift}}{\textit{Average power first shift}}; \quad (1)$$

$$R_{3-1} = \frac{\textit{Average power third shift}}{\textit{Average power first shift}}. \quad (2)$$

Ratios R_{2-1} and R_{3-1} take values in [0, 1] since the first shift is the period with the highest power request so as the lower the ratio, the more the difference among shifts.

It exists a significant difference among first and second shifts (see low ratios R_{2-1} in Table 1). This might be related to a different production load where large volumes are produced in the mornings. Also, different product types might require more/less intense operations. For instance, in the painting department, sanding operations are executed in the mornings because the waiting time between sanding and painting cannot exceed a certain limit to avoid oxidation. Sanding requires both high power and high volumes of compressed air, so that the ratio R_{2-1} is low for both painting and C12 compressed air system. Also, painting department does not work from 5pm to 10:30pm, differently from other departments. On the other side, ratio R_{2-1} is low also for machining department, but the reason is not straightforward and should be better investigated.

Among the power requests of first and third shifts, a significant difference is desired (i.e. low R_{3-1}), because it means that energy demand by night is low. However, ratios R_{3-1} in Table 1 are high for a high number of signals. This denotes high unwanted power requests during night periods. In offices the ratio is motivated by the request of IT server system which is always on. In painting department, dryers are required to work all night to dry the paint so that the power request is technologically motivated. Vice versa, for O2 building, the high ratios are unexpected and require a deeper investigation about the resources and the systems connected. Surely, the O2 compressed air system is often left on yielding to a supply exceed.

Table 1. Ratios of power requests using Monday to Friday data.

Description	R_{2-1}	R_{3-1}
Building C2	0.80	0.10
Building O2	0.89	0.43
Building C12	0.82	0.23
C2 Machining	0.78	0.10
C2 Offices	0.91	0.62
C2 Compressed air system	0.86	0.10
O2 Testing (new)	0.89	0.20
O2 Testing (old)	0.85	0.55
O2 Compressed air system	0.97	0.77
C12 Canteen	0.42	0.16
C12 Painting	0.50	0.30
C12 Testing	0.92	0.42
C12 Compressed air system	0.72	0.16
C12 Welding	0.96	0.19

The potential benefit of reducing the power consumption while the production is not required is clear by analyzing the fractions of energy consumed according to the periods (Table 2). By considering only weekdays (Mon-Fri), most of energy is used in the first two shifts. However, including the weekends (Mon-Sun), where the requests should be considered as non-productive shifts, the fraction becomes significant: respectively 0.12, 0.30, and 0.17 in C2, O2 and C12. Considering the overall factory energy consumption, around the 19% is allocated in non-productive periods.

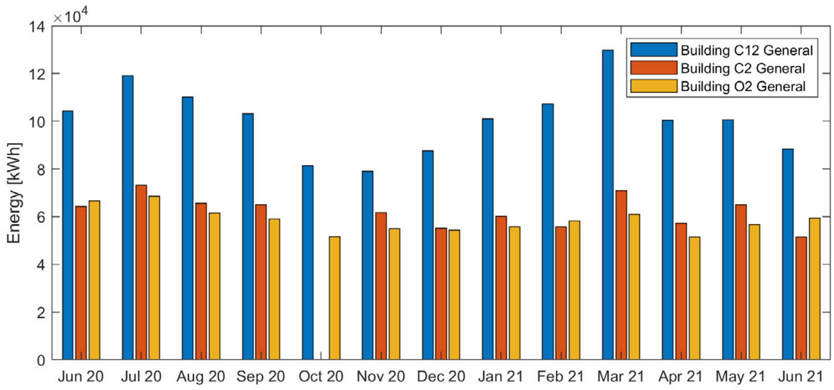

Fig. 2. General monthly energy consumption of the plant

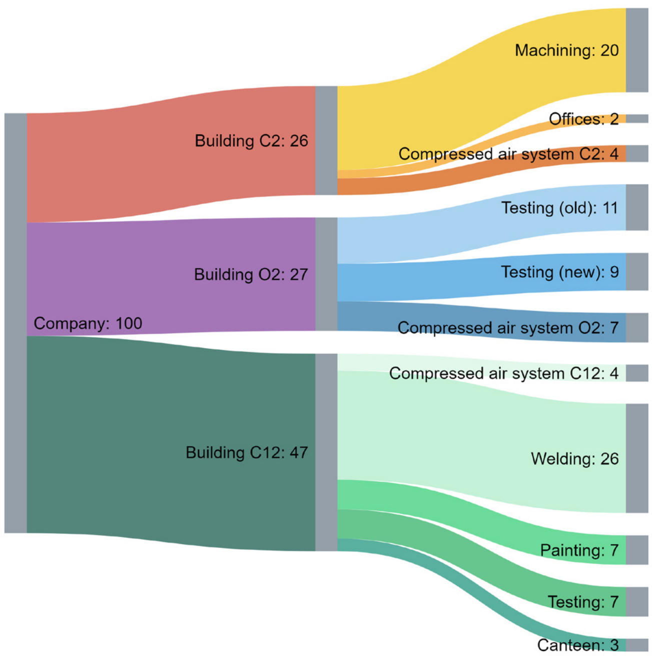

Fig. 3. Energy flows (values are expressed as percentage of the total)

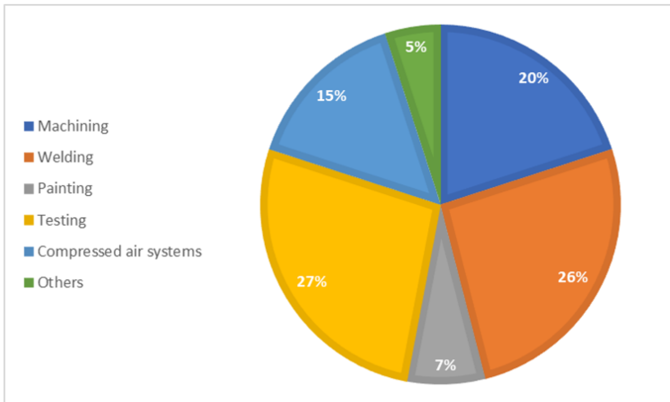

Fig. 4. Energy consumption distribution among departments. Others includes the canteen and the offices. Testing department also includes some offices.

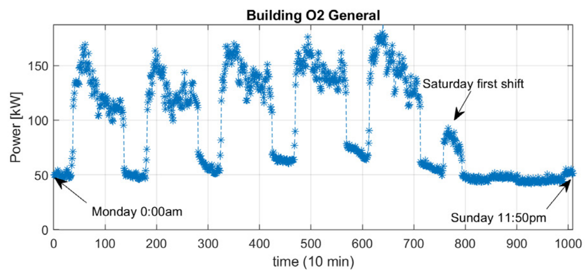

Fig. 5. Power request of O2 along acquired week n1

Table 2. Energy consumption fraction in productive and non-productive shifts.

Description	Shift I+II (Mon-Fri)	Shift III (Mon-Fri)
Building C2	0.94	0.06
Building O2	0.86	0.14
Building C12	0.90	0.10
Description	**Shift I+II (Mon-Fri)**	**Shift III(Mon-Sun) + I+II (Sat+Sun)**
Building C2	0.88	0.12
Building O2	0.70	0.30
Building C12	0.83	0.17

3.3. Analysis of power base load

Due to the Covid-19 pandemic emergency, Italy has imposed a lockdown during March-April 2020 so that industrial activities have been suspended. The company has closed during such period "switching off" the plant. Actually, the monitoring system was online and data are available so that the industry minimal power request can be extracted. Indeed, only minimal necessary plant services have been kept on during such period. Table 3 reports the ratios $R_{Covid19}$ among the average power requests during the Covid-19 closure period and the average power request of the typical first shift, as reference, so that the ratios can be compared with those of Table 1.

The high ratio recorded in Offices (i.e., 0.59) is related to power requested by IT servers and PCs (around 6 kW). Heating and ventilation systems have been maintained so that some

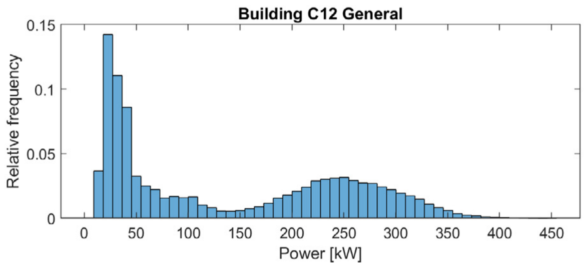

Fig. 6. Frequency histogram of the general power request in C2

Table 3. Ratios of power requests using data acquired during Covid-19 lockdown.

Description	$R_{Covid19}$
Building C2	0.06
Building O2	0.16
Building C12	0.06
C2 Machining	0.03
C2 Offices	0.59
C2 Compressed air system	0.04
O2 Testing (new)	0.09
O2 Testing (old)	0.36
O2 Compressed air system	0
C12 Canteen	0.07
C12 Painting	0.02
C12 Testing	0.16
C12 Compressed air system	0
C12 Welding	0.06

ratios are motivated. Heating and ventilation systems of C2 is connected under signal ”machining” so that, despite all machine tools have been switched off, the department maintains a small ratio. Similarly for welding and testing in C12. The high ratio in O2 testing-old (i.e., 0.36) is partially motivated by the HVAC (Heating, Ventilation, and Air Conditioning) systems and partially motivated by technical building services (water and nitrogen).

4. Data-driven monitoring system

Company's objectives are to monitor plant energy consumption, to map the efficiency of departments, to exploit the potentiality of energy efficient strategies, and to promptly reacts at production planning and control levels.

Monitored data are necessary to understand plant requirements in terms of energy consumption and to create a map of the more (or less) efficient areas of the plant so that specific measures can be implemented to increase factory energy-efficiency. The expected impact of the data-driven monitoring system is twofold: (1) monitoring factory energy usage, and (2) improving factory energy efficiency. The monitoring system should assist the energy referent of the industrial site to carry out automatic awareness tasks; hence to save time while significantly improving energy performance. For instance, by developing alarms on the areas that over consume.

To achieve the aforementioned impacts, the data-driven system has the following requirements:

- Collect, record and visualize energy consumption data;
- Compute energy-related KPIs (e.g., ratios R_{3-1}, R_{2-1}) to measure plant energy behavior;
- Integrate energy and production data for performance evaluation of plant energy efficiency;
- Identify critical situation for performance enhancement.

The integration among energy data and production data is crucial as highlighted in recent literature. In manufacturing, energy consumption of processes is highly dependent both from technology type, machines, product material and operation to be executed. To provide a simple example, roughing requires more power than finishing in machining; thus having a high power signal while performing roughing should not generate an alarm, whilst it should while finishing. As a consequence, a smart monitoring system must consider the actual production state of a resource. Scaling up at department level is highly complex. Information such as the number of active resources, the type of product in execution, and the need of auxiliaries are significant to be integrated with the power request data. In the case under investigation, the number of active painting cabins is significant as well as how many are devoted to sanding and drying, whereas the type of product seems to be not significant. The number of active testing cells is similarly significant. Welding and machining departments might require more information due to the variability of resources and processes.

The challenge is to integrate existing knowledge of the processes with collected data in an effective way so that plant efficiency mapping refers to a proper baseline helping the company in the understanding of efficiency according to the workload. Training and validation activities are required to create the reference baseline.

The smart data-driven monitoring system can be declined in two versions: off-line and on-line. The off-line version periodically exports, processes and analyses data proving an a-posteriori evaluation of the recorded period. The on-line version is continuously fed by data and the response is promptly provided. A set of methods for state identification and classification will be used to identify create a reference model of the plant, e.g. discriminant functions, probabilistic generative models, quadratic discriminant models, neural-networks, k-nearest neighbors models [10, 11, 12].

5. Final remarks and next steps

We concludes the analyses with a list of remarks:

- Power requests are significantly different among shifts;
- Power peak during the first shift is partially correlated to the HVAC systems and partially to the production activities, e.g. sanding operations in painting department;

- Unexpected power requests are recorded during non productive periods so that causes must be investigated (see Table 1 and Table 3);
- Painting department is virtuous: the power profile is technologically motivated and energy wastes are minimal by nights;
- Compressed air systems are significant energy-consumers and they often require high power despite air supply is not required.

The most critical situation is registered in O2 where ratio $R_{3-1} = 0.43$ indicated high unwanted power requests during non productive periods. Therefore, O2 will be treated with priority in the implementation of the energy monitoring system.

Data monitoring and data integration is crucial for the automatic recognition of suitable prognostics intervention toward more energy-efficient processes. A proper mapping of energy efficiency must be integrated with information related to production and machine load. Technological knowledge of the processes guides for a more effective selection of significant data.

Despite the power requests due to building systems that cannot be switched off completely, the evaluated ratios in Table 3 are significantly lower compared to Table 1 enhancing the potential savings during non productive periods. Considering the energy requests as in Table 2, the potential saving of switching off resources during not productive shifts (nights and week-ends) are up to 19%. Surely, such upper bound cannot be achieved because some resources and systems are active by night for technological reasons (IT servers, night dryers, etc.).

Future effort will be related to implement the energy monitoring system and to apply active actions for the reduction of energy consumption of the most critical departments. The use of recorded data, models, learning methods, and optimization algorithms should support the integration of acquired data and their actual use for decision making.

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