Energy Partnership Programme
between Indonesia and Denmark

Technology guideline for energy efficiency in compressed air systems

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Ministry of Energy and Mineral Resources Republic of Indonesia

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EMBASSY OF DENMARK Jakarta

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Ministry of Energy and
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Preface

Efficient energy use in the industrial sector, particularly through the integration of energy-efficient technologies, has become increasingly critical in the global endeavour to promote sustainability and climate resilience. Industries globally accounted for 37% (166 EJ) of global energy use in 2022, making them a crucial focus area for energy efficiency efforts. According to the International Energy Agency (IEA), industrial motors and drives alone are responsible for about 40% of industrial electricity consumption, with air compressors accounting for 7% of industrial electricity consumption, according to an estimate made by Danish Energy Agency (DEA) for this guideline. This emphasizes the urgency of adopting energy-efficient technologies to mitigate climate change impacts.

In Indonesia, the industrial sector currently accounts for around 43% of the country's total energy consumption, and projections suggest a doubling of energy demand by 2050 without intervention. Within this context, widespread adoption of energy-efficient technologies related to compressed air systems and other equipment emerge as a crucial strategy to alleviate energy burdens, enhance sustainability, and bolster resilience against escalating energy demands.

In Denmark, the strategic adoption of energy-efficient technologies has been instrumental in achieving remarkable reductions in industrial energy consumption. Denmark ranks among the most energy-efficient countries in the world, with the second-lowest energy intensity across all sectors in Europe, indicating significant improvements in energy efficiency relative to GDP output.

Recognizing the urgency of addressing energy-saving potentials in the industrial sector, the Danish Energy Agency (DEA) and the Danish Embassy, in collaboration with the Directorate of New Renewable Energy and Conservation (EBTKE), Ministry of Energy and Mineral Resource (MEMR) in Indonesia, are in partnership through the Indonesia-Denmark Energy Partnership Programme (INDODEPP). One of the deliverables under INDODEPP is the development of a Technology Guideline for Industrial Applications, focusing on energy-efficient compressed air systems as part of the activities.

To ensure the accuracy and relevance of the Technology Guideline in an Indonesian context INDODEPP first conducted a Scoping Study Meeting to discuss scope, methodologies, content and data for the development. The first draft of the Technology Guideline was then presented and discussed at a Consultation Workshop with key stakeholders, including relevant line ministries, institutions, agencies and associations involved in the industrial sector in Indonesia. The Consultation Workshop provided crucial local insights, enhancing the report's credibility and utility for Indonesian stakeholders.

The overall aim of the Technical Guideline is to describe solutions and measures to address when planning and installing new compressed air systems or when planning to rehabilitate existing systems.

The guideline aims at creating an understanding of energy efficiency questions for compressed air systems used for a wide range of purposes incl. trainings and capacity development activities.

Besides covering energy efficiency questions, the guideline also aims to create understanding when sourcing new equipment; what should be considered when buying new equipment and the procurement process.

The Technical Guideline has the following sections:

- Section 1: International Experience
- Section 2: National perspectives in Indonesia
- Section 3: Compressed air technology in brief
- Section 4: Improving energy efficiency in compressed air systems.
- Section 5: Selection and Specification of New Compressed Air Installations.
- Section 6: Examples from energy audits of Indonesian, Vietnamese and Danish industry
- Section 7: The procurement process for new compressed air systems.

In the appendix of the catalogue, more detailed information can be found:

- Appendix 1: Checklist for energy optimization of compressed air systems

The catalogue further describes cases for rehabilitating compressed air installations as well as the business case for replacing old inefficient systems with new high-efficiency ones.

Acknowledgements

The Technical Guideline for Compressed Air Systems is part of a collaborative effort under the Government-to-Government (GtG) between Indonesia and Denmark namely the Indonesia-Denmark Energy Partnership Programme (INDODEPP) through the Danish Embassy Jakarta and Danish Energy Agency (DEA) and the Directorate of Energy Conservation through the Directorate General of New, Renewable Energy, and Energy Conservation (EBTKE) at the Ministry of Energy and Mineral Resources (MEMR).

The technical guidance builds on the work of the long-standing expertise of global corporation at the Danish Energy Agency (DEA) with partnered countries and was prepared by the DEA with support from the Viegand Maagoe International Consulting Firm.

The work was made possible thanks to a dedicated contribution from all the involved stakeholders in Indonesia from government entities, industrial players, industrial and technology associations, development partners, and industrial electric motors technology providers.

The development of Technical Guidance was led by Nadeem Niwaz and co-contributor, namely Paolo Zuliani from Danish Energy Agency. The key authors of this guideline were Peter Kristensen (Chief Advisor) and Emil Rosendal Albæk (Project Manager) from Viegand Maagoe. Supportive assistance was given by Sandra Pratiwi (Energy Consultant) at the Danish Embassy Jakarta for liaising with national partners in ensuring a streamline process of the development. The report would not have been possible without the technical and strategic support from Rusmanto from PT Langgeng Ciptalindo. The authors would also like to express their gratitude to the team led by Mr. Hendra Iswahyudi, Director of Energy Conservation; Team Nurcahyanto, Wisnu Adi Purwoko, Wijaya Ikhlasa Rajasa, and Arman; as well as Team Endra Dedy Tamtama of EBTKE, Ministry of Energy and Mineral Resources, for their guidance, input, and advice.

The authors would also like to thank the people who contributed to the document by providing local insights and data by engaging and participating in the previous stakeholder meeting and consultation that were held in February 2025 for scoping the guideline outlines and May 2025 for the consultation workshop on the preliminary draft of the technical guideline. Thanks also to the DEA Communications Department for their help in featuring the guideline on the DEA's website and social media, as well as to the EBTKE Communication Team for their support in publishing the report at the MEMR One-Stop-Shop (OSS), SINERGI.

Executive summary

In Indonesia, the electricity consumption for compressed air systems (CAS) accounts for around 7% of the total industrial electricity consumption with the consumption projected to increase in the coming years. Based on scenarios developed by the DEA for the electricity consumption of CAS up to 30 TWh in energy savings can be achieved, if a high-ambition scenario becomes reality compared to a business-as-usual scenario. The high-ambition scenario requires a significant focus on energy efficiency measures for CAS but can also potentially offset (e.g. up to 5 GW) construction of new power generation capacity

With the increased demand for energy-efficient technologies, a guideline focusing on compressed air systems and the efficiency of these has been developed as part of the collaboration between the Danish Energy Agency (DEA) and the Danish Embassy, the Directorate of New Renewable Energy and Conservation (EBTKE), Ministry of Energy and Mineral Resource (MEMR) in Indonesia, in a partnership through the Indonesia-Denmark Energy Partnership Programme (INDODEPP).

This guideline describes national and international experiences and perspectives with a description of both standards for increasing efficiency of CAS, regulatory frameworks and financial schemes supporting the increase of energy efficiency.

The guideline also contains a summary of different types of air compressor systems, applications, design recommendations when selecting new equipment and recommendations for the procurement process. Furthermore, the guideline contains examples of energy saving projects related to CAS. Based on these 9 examples implemented at Indonesian enterprises, one for a Vietnamese enterprise and one for a Danish enterprise, which includes e.g. Artificial Intelligence (AI) control, Variable Speed Drives (VSD) on motors and heat recovery, showing that typical CAS energy saving projects can achieve a payback time of 1-6 years.

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1 International experience

1.1 Examples of international best practices to promote energy efficiency

Until the introduction of the **ISO 11011** standard for assessing and auditing compressed air systems in 2013, there was no formal standard for conducting an audit for compressed air. The audit introduced standardized methods for assessing the current state of a given compressed air system, which was classified into the three subsystems covering the air supply itself (conversion from primary energy to compressed air), transmission (moving compressed air from generation point to area of use) and demand (end-use application and forms of compressed air waste). The standard sets requirements for data analysis, reporting and documentation and estimation of energy saving potentials from the assessment. The majority of the topics covered in the standard are also coved in this guideline, and while the standard is the first formal standard of its kind regarding compressed air systems, many of the recommendations included have been common practice during compressed air audits for several years.

Some of the key topics included in the ISO-standard, which are also treated in this guideline, are listed here:

- Compressed air treatment; included in section 4.5
- Compressed air point of use; included in section 4.1
  Compressed air systems and control; included in section 4.3
- Transmission; included in section 4.6.1
- Demand/supply flow rate and pressure set point; included in section 4.2
- Pressure set point; included in section 4.2
- Compressed air storage; included in section 4.2.2
- Assessment methodology and checklists; included in chapter 4
- Heat recovery; included in section 4.4
- Leakage detection and maintenance; included in section 4.6

1.2 Incentives schemes for Promoting Efficient Compressed Air Systems (CAS)

In general, the biggest incentive focusing on energy efficiency of compressed air systems is reduced electricity consumption, which can both reduce operational costs and potentially CO_2-emissions. In Denmark, energy saving measures have been subsidized since the 1990's. The subsidy schemes have been structured differently over time. What they have in common is that the subsidy was related to the investment in energy-saving equipment. Some of them have also provided subsidies for the reduction of CO_2 emissions, and thereby for equipment that replaces fossil fuels with renewable energy sources or electrifies the processes.

Incentive schemes play a crucial role in accelerating the adoption of energy-efficiency measures e.g. within compressed air systems in the industrial sector. These schemes can help overcome economic barriers by making the transition to efficient equipment more financially attractive. This subchapter explores various types of incentive mechanisms, supported by case studies that illustrate successful implementations globally.

1.2.1 *Voluntary Agreement Schemes (VAS)*

Below are the two (2) examples of the incentive scheme:

1) Denmark's Voluntary Agreement Scheme (VAS). A Voluntary Agreement Scheme (VAS) is an effective approach to incentivize the energy intensive industries implementing energy efficiency

projects. In a VASsdustrial sectors, which are a form of VAS aimed at enhancing energy efficiency. One notable outcome of these agreements is that participating companies The Dutch government supported this initiative by providing incentives, such as tax benefits and technical assistance, encouraging industries to invest in high efficiency equipment. More than 1,000 companies across 37 sectors have engaged in these agreements, contributing significantly to the Netherlands' national energy goals.

1.2.2 *Performance-Based Financing Schemes*

Performance-based financing schemes encourage the adoption of energy-efficient technologies by structuring financial incentives around the realized energy savings of a project. In these schemes, payments are tied directly to the performance of the installed equipment, such as improving energy efficiency of compressed air systems, which allows companies to offset the initial investment through future energy savings. This model reduces financial risk for participants by requiring minimal or no upfront costs and enables a practical way to fund energy efficiency improvements in capital-intensive sectors.

1.2.3 *Investment Subsidy Schemes*

Investment subsidies are another popular incentive type that directly targets energy efficiency upgrades, such as replacing standard motors with premium efficiency ones. These schemes typically provide financial support to cover a percentage of the investment cost, lowering the initial financial burden for companies and improving project viability. In Denmark, such a scheme has existed on several occasions—initially financed through the utility companies, and now directly from the state budget.

1.2.4 *Tax Incentive Schemes*

Tax incentive schemes provide reductions in corporate tax rates or tax credits for companies investing in energy-efficient technologies. These schemes can serve as a substantial motivator for industrial facilities to transition to more energy efficient equipment. The following case study showcases tax break programme provided by the UK government on energy efficient investments on several significant energy users equipment, including motors. **United Kingdom's Enhanced Capital Allowances**

The United Kingdom has implemented a successful tax incentive program called the Enhanced Capital Allowances (ECA), which encourages businesses to invest in energy-saving plant and machinery. The ECA scheme allows businesses to write off 100% of the investment cost of qualifying equipment against their taxable profits in the financial year of purchase. This immediate tax relief accelerates cost recovery and provides a substantial financial incentive for adopting energy-efficient technologies.
Manufacturers can apply to have their products included on the Energy Technology Product List shown as follows:

- Motors and drives
- Air-to-air heat recovery
- Automatic monitoring and targeting (AMT) equipment
- Boiler equipment
- Combined heat and power (CHP)
- Compressed air equipment
- Heat pumps
- Heating, ventilation and air conditioning (HVAC) equipment
- High speed hand air dryers
- Lighting
- Pipework insulation
- Refrigeration equipment
- Solar thermal systems
- Uninterruptible power supplies
- Warm air and radiant heaters
- Waste heat to electricity conversion equipment

The programme provides an incentive for manufacturers to develop more efficient products, since inclusion can increase the financial return on their equipment and hence boost sales. Of course, for Enhanced Capital Allowances to be effective the company purchasing the equipment must be liable to pay corporation tax, otherwise there is no effect. The UK Enhanced Capital Allowance scheme was introduced in 2001 and an independent evaluation carried out in 2008 indicated that companies that were aware of the scheme tended to invest more in energy efficiency

1.2.5 *Grants and Rebate Programs*

Grant and rebate programs are designed to encourage businesses to invest in efficient technologies by offering direct financial incentives post-purchase or after project implementation. These incentives are generally simpler and quicker for companies to access compared to tax incentives. The country that has already implemented this scheme is as follows:

Chile's electric motor grants

The industrial and mining sectors account for about 38% of primary energy consumption in Chile. These sectors are heavily dependent on small motors for various tasks such as material handling and processing minerals. In 2009 Chile initiated a programme to encourage the replacement of traditional motors with high efficiency motors. With a total budget of USD 2.5 million the programme subsidised the purchase of high efficiency motors to equalise their cost with conventional units. The scheme covered motors up to 7.5 kW and in 2009 and 2010 over 5,000 motors were replaced.

1.2.6 *Complementary Financing Programs*

In addition to incentive schemes, larger programs such as Indonesia's Just Energy Transition Partnership (JETP) can help mobilize substantial financing for energy transition efforts. JETP aims to secure international support and investments, including the promotion of energy-efficient technologies in the industrial sector. Such programmes align with Indonesia's commitment to achieving net-zero emissions and improving energy security.

1.3 Carbon Border Adjustment Mechanism (CBAM)

The EU's Carbon Border Adjustment Mechanism (CBAM) is a key instrument designed to place a fair price on the carbon emissions associated with the production of carbon-intensive goods imported into the EU. Its aim is twofold: to prevent carbon leakage and to promote cleaner industrial production in non-EU countries.

The overarching objective is to drive CO_2 emission reductions - both direct and indirect - within carbon-intensive industries, both inside and outside the EU. The less action a company takes to reduce CO_2 emissions, the higher the cost of exporting goods to the EU. Improving the energy efficiency of systems such as compressed air can be a valuable part of emission reduction strategies for these industries.

2 National perspectives in Indonesia

2.1 Regulatory status

A key regulation guiding energy efficiency efforts in Indonesia is Government Regulation No. 33 of 2023. This regulation introduces mandatory requirements for the implementation of energy audits in designated sectors and establishes Minimum Performance Standards for Equipment (Standar Kinerja Energi Minimum – SKEM). These standards aim to promote the adoption of energy-efficient technologies and practices across industries by setting minimum energy performance criteria for key equipment.

The regulation also outlines responsibilities for both the government and energy users, including the reporting of audit results and the implementation of recommended efficiency measures where feasible. This creates a structured approach to improving energy performance at the national level.

In addition to national regulations, international standards such as ISO 50001 on Energy Management Systems offer complementary frameworks that organizations can adopt to enhance their energy performance systematically. These standards help align national efforts with global best practices and support continuous improvement in energy management.

Currently, there are no Indonesia-specific standards and regulations regarding Compressed Air Systems (CAS) , and Indonesia has adopted standards from USA, Europe and the ISO-standards (such as ISO 11011 mentioned in section 1.1. The only regulation concerning compressed air is the 'Ministry of Manpower No. 37 2016, Health, Safety, and Environment – Pressure Vessel' which is mostly related to safety around compressed air and pressure vessels.

2.2 Observations in Indonesian industry

From energy audits conducted in the Indonesian industry, significant energy saving potentials have been observed, by example the following:

- Large potential in regularly detecting and repairing air leaks
- Oversized compressors leading to inefficient operation.
- Inappropriate use of compressed air in processes.
- Non-optimal control strategies in the compressor central.

For such reasons, it must be expected that auditing of air compressed systems can achieve significant energy savings.

2.3 Share of industrial electricity consumption

According to the latest RUKN conducted industrial electricity consumption in Indonesia could exceed 774 TWh by 2060. This estimation considers only the electricity consumption of industrial electrical appliances and does not include any process heating components powered by electricity.
The total industrial electricity demand can be broken down into the following major appliance categories:

1) **Electric motors:** convert electrical energy into mechanical energy through electromagnetic induction. They are widely used in various sectors, including industry, transportation, and consumer electronics. Modern electric motors emphasize energy efficiency, compact designs, and advanced control systems to optimize performance and durability

2) **Chillers:** Refrigeration systems used to remove heat from liquids or air. They are commonly employed in industrial processes and Heating Ventilation and Air-conditioning (HVAC) systems to maintain temperature control. Chillers use compressors, condensers, and evaporators to achieve cooling by circulating refrigerants.

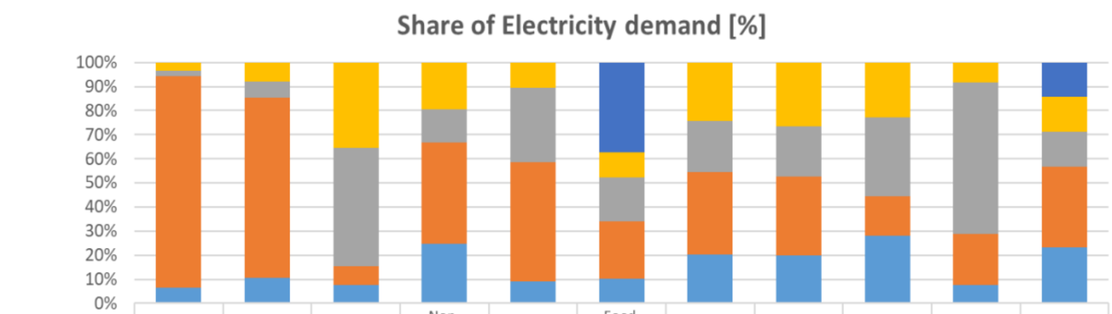
3) **Fans and pumps:** Fans circulate air, while pumps move liquids or gases. Both use electric motors to drive their operation. Technologies such as variable-speed drives allow precise control of flow

rates, improving efficiency and reducing energy consumption in industrial and commercial applications

4) **Lighting:** Modern lighting technologies include Light Emitting Diodes (LEDs), which are highly energy-efficient compared to traditional incandescent or fluorescent lights. LEDs offer longer lifespans, better light quality, and lower power consumption, making them ideal for residential, commercial, and industrial use.

5) **Air compressors:** convert mechanical energy into potential energy stored in compressed air. They operate using positive displacement (e.g., piston or rotary screw) or dynamic displacement methods. Compressed air is used in various applications like powering pneumatic tools or industrial processes

Previous technology guidelines of the Danish Energy Agency have estimated that implementing a Minimum Energy Performance Standard (SKEM) for electric motors could result in energy savings of approximately 100 TWh by 2060. A similar approach has been applied to air compressors, where various energy-saving measures have been identified and assessed in terms of their potential impact. Figure 1 illustrates the share of electricity consumption attributed to five major end uses—cooling, air compressors, fans and pumps, motor drives, and lighting—across various industrial sectors. Motor drives represent the dominant share in most sectors, especially in iron and steel, non-ferrous metals, and textiles, while other end uses vary significantly by industry.



	Iron and steel	Non ferrous metals	Chemical	Non-metallic mineral products	Pulp, paper and printing	Food, beverages and tobacco	Transport Equipment	Machinery Equipment	Textiles and leather	Wood and wood products	Other Industrial Sectors
Cooling	0.00%	0.00%	0.00%	0.00%	0.00%	37.20%	0.00%	0.00%	0.00%	0.00%	14.42%
Air Compressors	3.51%	7.82%	35.54%	19.64%	10.67%	10.43%	24.44%	26.69%	23.02%	8.44%	14.33%
Fans and Pumps	2.19%	6.96%	49.14%	13.73%	30.86%	18.33%	21.00%	20.55%	32.37%	62.88%	14.59%
Motor Drives	87.72%	74.61%	7.91%	42.02%	49.23%	23.97%	34.30%	32.98%	16.55%	20.92%	33.60%
Lighting	6.58%	10.61%	7.41%	24.61%	9.25%	10.07%	20.26%	19.78%	28.06%	7.76%	23.06%

Figure 1: Breakdown of electricity demand by end-use category across industrial sectors in Indonesia based on European data and experience [7]

The distribution of electricity consumption among different industrial appliances has been estimated based on European industrial energy demand shares provided by the JRC (Joint Research Centre).

Air compressors, in comparison, consume significantly less electricity than motors, with current electricity consumption estimated at 18–20 TWh. This demand is expected to increase to approximately 80 TWh by 2060.

The primary industries relying on air compressors include the Chemical industry, Food & beverage industry, Textile industry and Transport equipment manufacturing.

Among these, the Food & beverage and Chemical industries account for nearly 50% of total air compressor electricity consumption. Other sectors have a lower share of compressor usage.

2.4 Impact of energy efficiency measures in the Indonesian industry

The technology guideline for air compressors has identified four key energy-saving measures that could significantly reduce electricity consumption:

1) Elimination of the Component: This involves identifying and removing unnecessary air compressors from the system. In some cases, alternative devices can perform the same function more efficiently, eliminating the need for compressed air entirely.

2) Fixation of Air Leakages: This refers to the process of detecting and repairing leaks in the compressed air system. Air leaks are a significant source of inefficiency in compressed air systems, wasting energy and reducing overall performance.

3) Pressure Adjustment: This involves optimizing the operating pressure of compressors. When high pressure is not required for specific applications, lowering the pressure can reduce energy consumption. This can be done by adjusting the pressure regulator on the air compressor.

4) Replacement with More Efficient Equipment: This strategy involves upgrading old compressors with newer, more efficient models. Modern compressors are often designed to be more energy-efficient and can be properly sized to match the specific requirements of the process, avoiding unnecessary energy consumption.

Every energy saving measure has an energy saving potential, which refers to the amount of energy that can be saved by implementing specific energy efficiency measures in industrial processes or appliances. It represents the theoretical maximum reduction in electricity consumption that can be achieved if the measure is fully applied. Further, potential penetration in the context of energy efficiency measures refers to the extent or proportion of the total potential market or application where a specific measure or technology is adopted or implemented.

The energy efficiency improvement potentials presented have been estimated based on useful energy analyses conducted exclusively within the Food and Beverage and Pulp and Paper sectors. Consequently, these estimates do not directly include other industrial categories, such as Energy Intensive Industries. To extend the application of these potentials to a broader industrial context, certain methodological assumptions are adopted: data and results obtained from the Food and Beverage sector are considered representative of other "standard" industries and are subsequently generalized to the entire industrial sector.

This generalization is supported by energy audits conducted at the European level, which have highlighted similarities across the years in energy saving measures and efficiency improvement opportunities coming from expert judgments from involved consultants, based on in-depth technical knowledge and extensive experience in relevant industrial sectors.

Therefore, despite originating from a sector-specific analysis, this approach enables the provision of a reliable and consistent estimate of energy efficiency potentials applicable across a wider range of industries.

Table 1: Energy saving potential and penetration potential for every behavioural measure discussed within the technology guideline according to expert judgement and experience from energy audits conducted in Indonesia

Measure	Potential	
Energy saving	**Energy Saving**	**Penetration**
Pressure adjustment	10%	30%
Air Leakage	25%	30%
Replacement	30%	20%
Elimination	100%	20%

Based on the penetration rates in Table 1 , different scenarios have been developed to assess the potential impact of energy-saving measures on industrial electricity consumption. These scenarios will be discussed in subsequent chapters.

2.4.1 *Scenarios*

Adoption rate measures how quickly a new energy saving measure is embraced and used by a group of people or organizations. It reflects the pace at which energy saving measures spread through a society and are adopted over inefficient practices.

Three different energy scenarios were developed: Business-as-Usual (BAU), Low Ambition, and High Ambition.

1) **Business-as-Usual (BAU) Scenario** – This scenario assumes that no additional energy-saving measures are implemented beyond existing policies and market trends. Industrial electricity consumption follows its natural trajectory without significant efficiency improvements.

2) **Low Ambition Scenario** – In this case, energy-saving measures are applied, but only 50% of the adoption rate is realized. This represents a moderate level of intervention, where some efficiency improvements are adopted, but market, regulatory, or technical barriers limit full implementation.

3) **High Ambition Scenario** – This scenario assumes 90% of adoption rate is achieved. It reflects a future where strong policies, incentives, and industrial best practices drive near-complete implementation, significantly reducing electricity consumption in the industrial sector.

By comparing these scenarios, the potential impact of different levels of ambition in energy efficiency adoption can be assessed, providing insights into how industrial electricity consumption could evolve under varying policy and market conditions.

Table 2: Adoption rate trend as a function of scenarios and energy saving measure.

	Adoption rate		
Energy saving measure	**BAU**	**Low Ambition**	**High Ambition**
Pressure adjustment	0%	50%	90%
Air Leakage	0%	50%	90%
Replacement	0%	50%	90%
Elimination	0%	50%	90%

2.4.2 *Results*

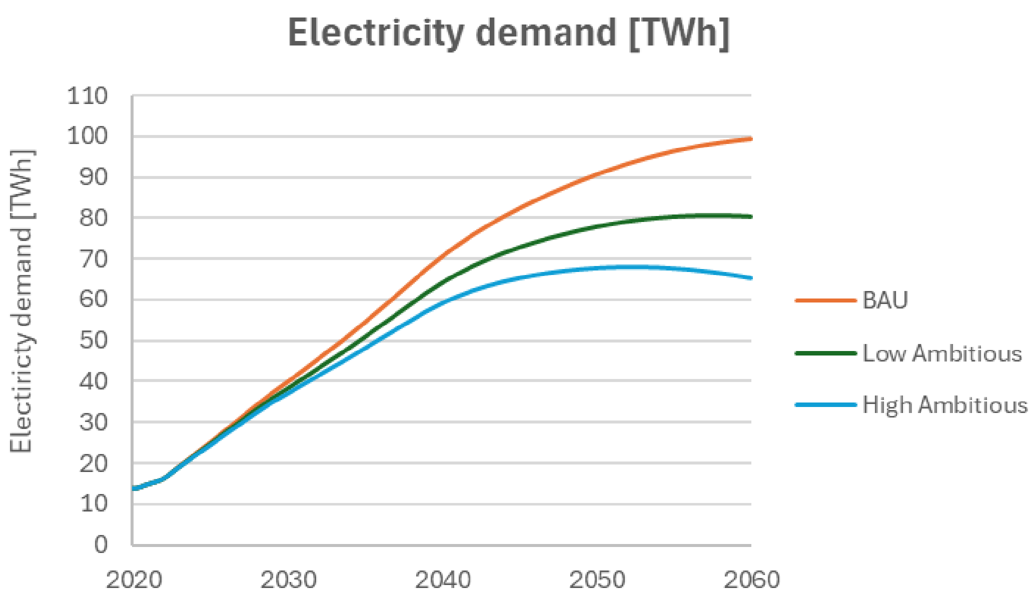


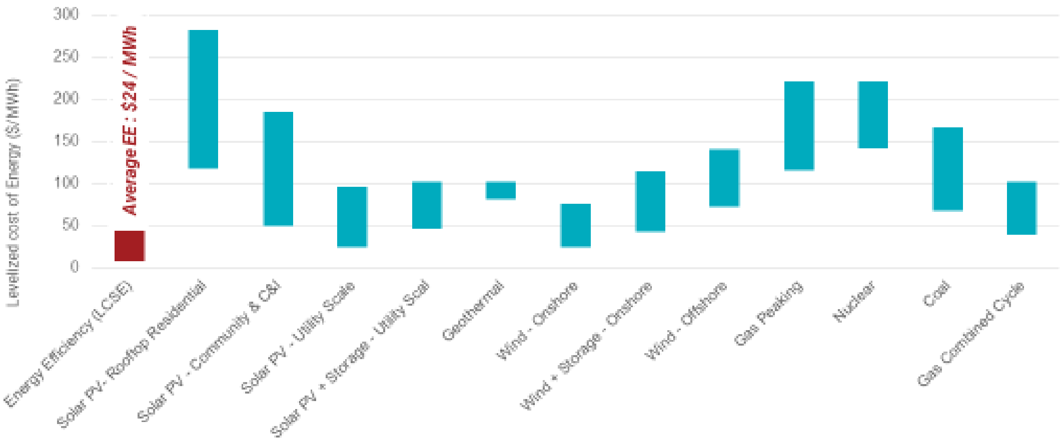
Figure 3: Electricity demand of the air compressors system in 3 scenarios: Businness as Usual (BAU), Low Ambitious, High Ambitious

The energy-saving potential of air compressors remains particularly relevant for three key industrial sectors: textiles, food and beverage, transport and chemicals.

In the Business-as-Usual (BAU) scenario, electricity consumption from air compressors is projected to reach 100 TWh by 2060. However, under the High Ambition scenario, this consumption could be reduced to approximately 65 TWh. In total, the air compressors account for 7% of total industrial electricity demand, achieving a 35 TWh reduction in electricity demand translates into substantial environmental and economic benefits. For example, this amount of energy is equivalent to avoiding the need for approximately 500 km² of solar panels (approximately 5.5 million badminton courts), assuming an average solar irradiance of 1,700 kWh/m²/year, a solar panel efficiency of 20% and a capacity factor of 18%. Another example is offsetting the output of 6 GW of coal-fired power capacity a capacity factor of 50%, resulting in a CO_2 emissions reduction of about 27 million tons, assuming coal power plants emit 900 g CO_2/kWh.

These findings underscore the critical importance of enhancing the energy efficiency to realize significant electricity savings and reduce environmental impacts. It is generally acknowledged that implementing energy efficiency measures tends to be more cost-effective than investing in new energy supply capacity. In general, installing energy efficiency measures is cheaper than installing new power generation capacity. Although wind power and utility-scale solar are becoming increasingly competitive, energy efficiency remains, in most cases, the most economical option. Including this perspective further supports prioritizing efficiency improvements as a key strategy for sustainable industrial energy management.

Cost of saved energy is lower than electricity generation



3 Compressed air system technology in brief

3.1 Compressed air systems

A compressed air system consists of a wide range of equipment as shown in Figure 5 .

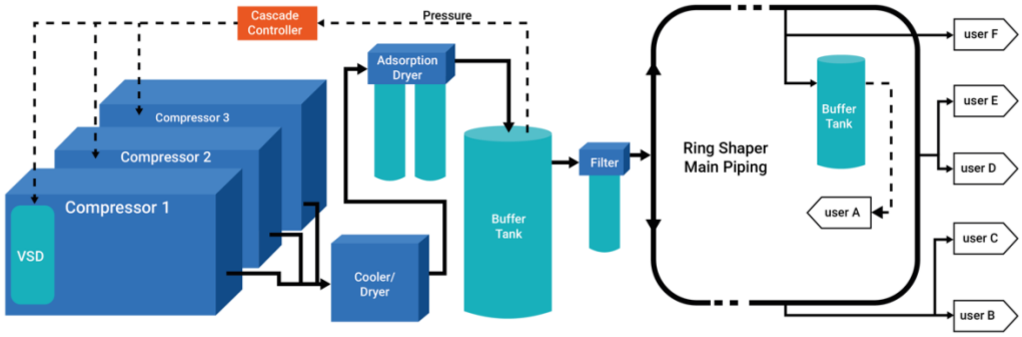


Figure 5: Schematic of air compressor system with key components Compressed air can be used for many applications and processes in a factory, e.g.:

- Tool powering
- Control and actuators
- Conveying
- Cleaning
- Cooling
- Etc.

Compressed air has the advantage of being useful for many applications, and the air compressors and the system is simple in installation and reliable in operation. Furthermore, compressed air also reduces a possible explosion risk, since sparks from air driven tools are avoided.

However, there is one large disadvantage: Air compressors are highly inefficient. Approximate 8-15% of the input energy is converted to work at the end user. The rest of the input energy is converted to excess heat.

Since compressed air is so inefficient combined with the fact that more efficient solutions exist there is a large potential in investigating the current state of the compressed air system and reduce the need, as large energy savings can be achieved.

3.2 Compressors

Selecting high-efficiency compressors is important, but as long as modern types from recognized manufacturers are chosen, the other factors lined up in this document are more important. Figure 15: presents recommended specific energy use at different pressure levels. For a system pressure of 7 bar(g) it is possible to reach a total specific consumption 0.10 kWh/Nm^3 for the central in total with the correct dimensioning and control. In this context, a suitable target is to select compressors with a specific energy consumption no greater than 0.10 kWh/Nm^3 at the specified system pressure and maximum flow rate.

3.2.1 *Common compressor types*

The absolute dominating types of compressors are screw-, reciprocating- and vane compressors, with screw compressors of the two types: lubricated and oil-free.

The energy efficiency at maximum capacity does not vary a lot for different compressor types. However, when measuring energy consumption per m^3 air over time, the specific energy consumption can vary significantly between compressor types, primarily due to differences in idle electricity consumption.

Efficiency is defined as the “specific energy consumption” [kWh/m^3] = Electrical energy for compressor divided by the air volume (before compression) - volume here is at the conditions for the inlet air.

Typical values for the “specific energy consumption” at on/off operation are indicated in :

Table 3: Different compressors and their specific energy use at 7 bar(g). For other pressure levels see Figure 15 .

Compressor types	Specific Energy consumption @7bar(g) [kWh/Nm3]	Idle load % of full load
Lubricated screw compressor	0.10	20 – 25
Oil-free screw compressor	0.10 - 0.11	18 - 20

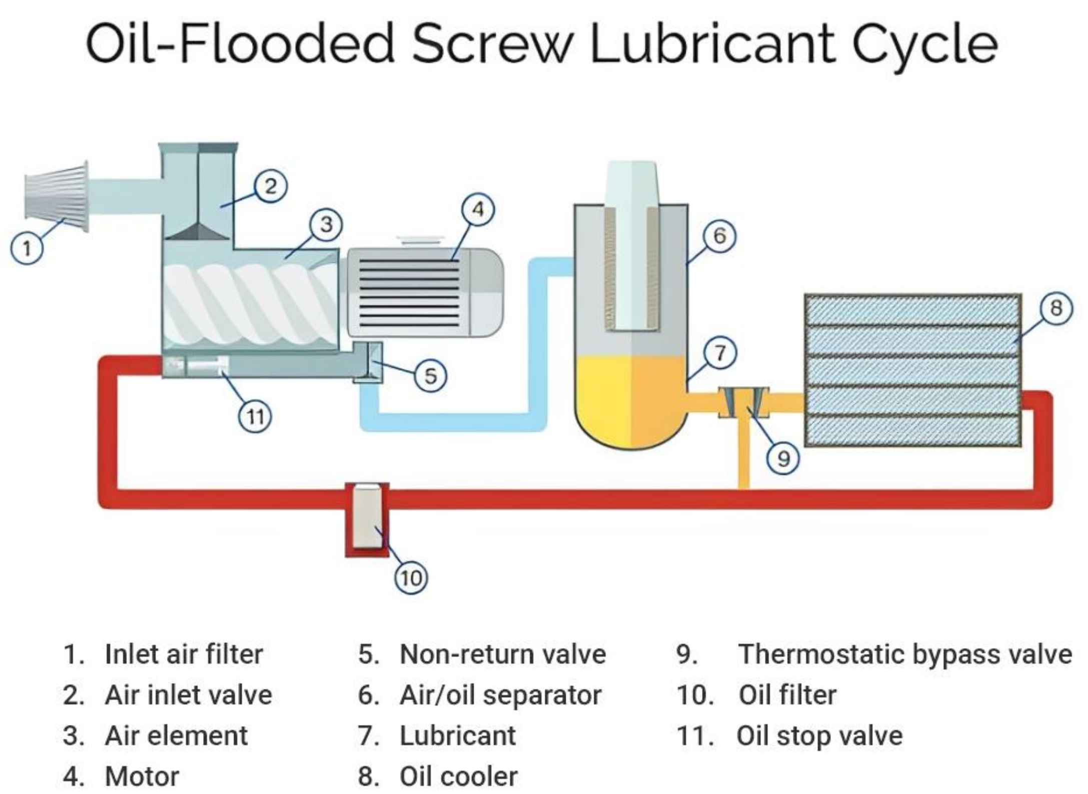


Figure 6 : Illustration of lubricated screw compressor.
Source: airbestpractices.com

1.Intake air
2.Reverse osmosis water
3.Water supply reverse osmosis
4.Drain water reverse osmosis
5.Compressed air
6.Primary water fow

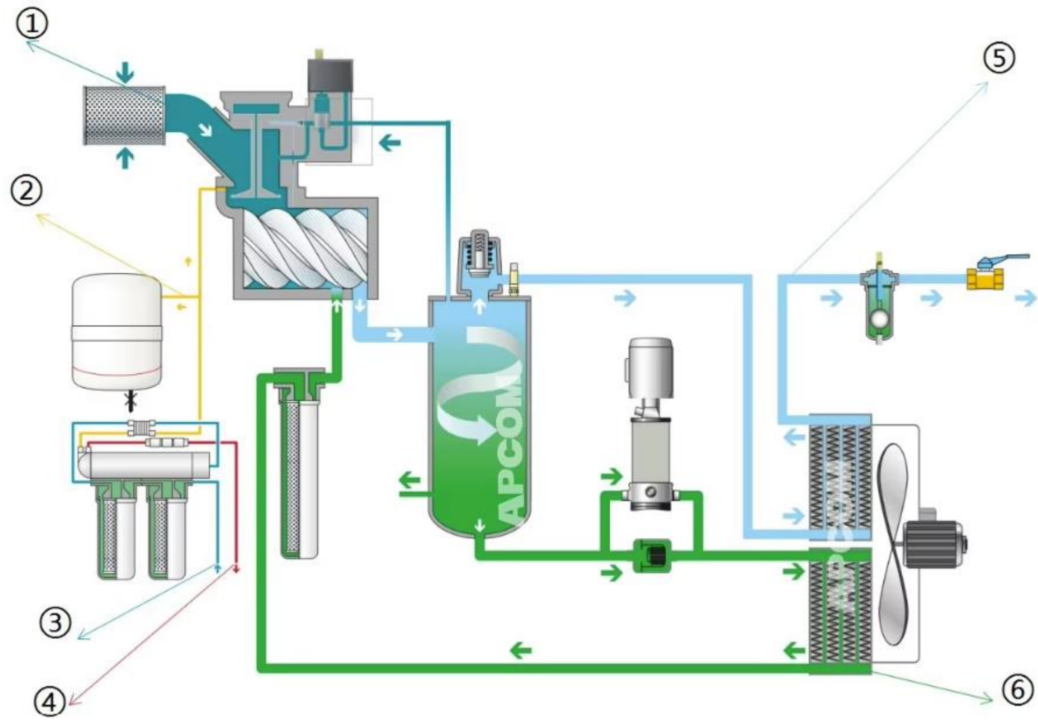
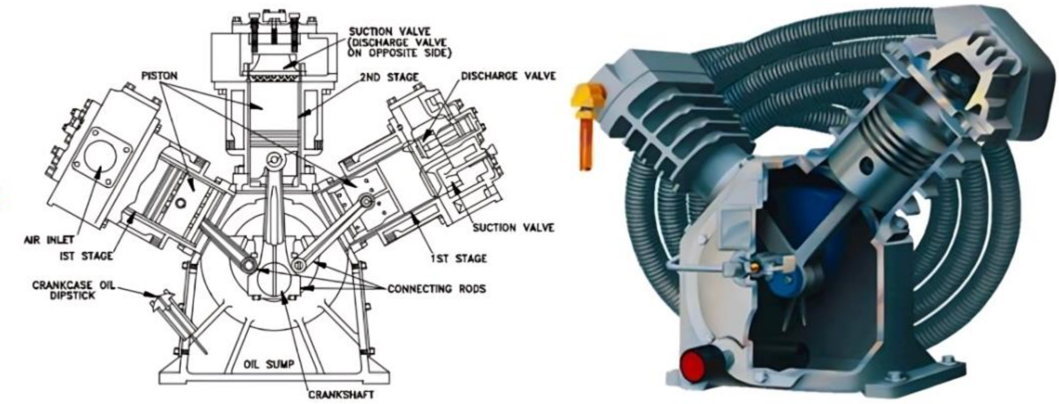


Figure 7 : Oil-free screw compressor.Source: Atlas Copco

Reciprocating – 2 stages	0.11	12



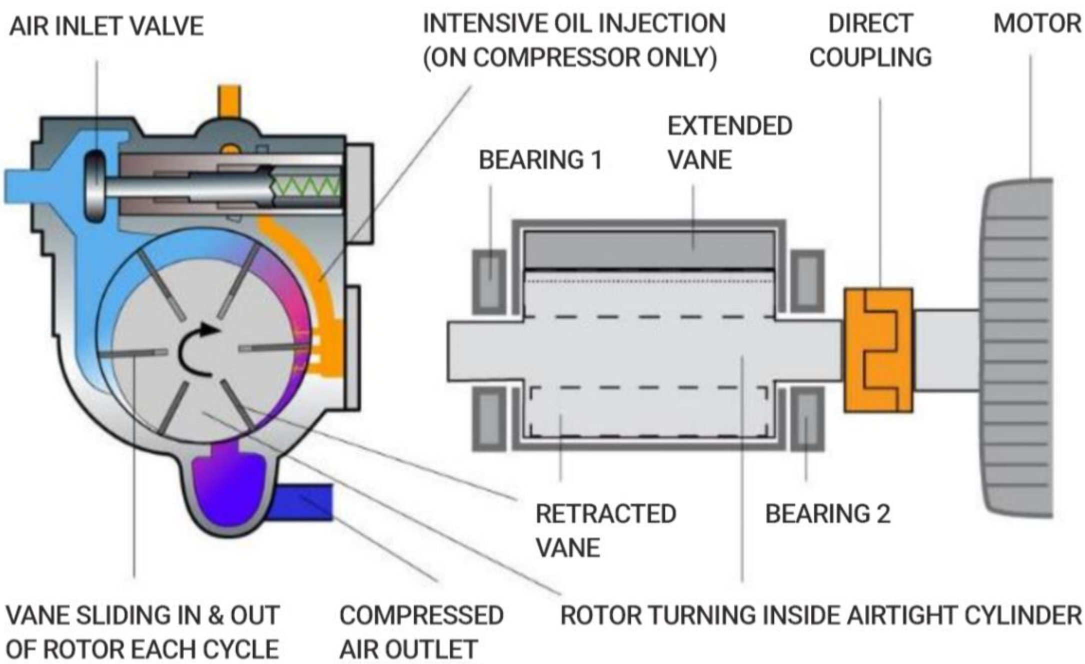


Figure 8 : Reciprocating compressor. Source: Aivyter.com

Rotary vane compressor	0.12 - 0.13	40

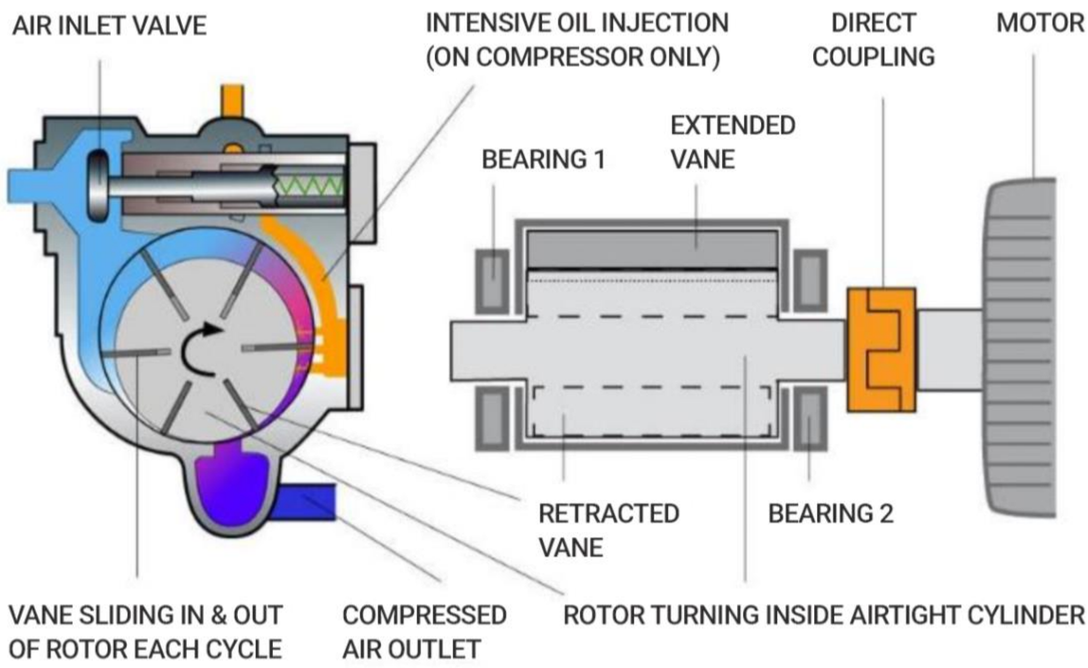


Figure 9 : Rotary vane compressor. Source: pneumofore.com

In the table above - notice the different power in % of full power used for compressors running idle load:

- Lubricated screw compressor: 20-25
- Oil-free screw compressor: 18-20
- Reciprocating compressor: 12
- Rotary vane compressor: 40

During these idle periods, air compressors still consume electricity. The percentage of full power used at idle reflects how much energy is being wasted when no useful work is being done. Compressors with high idle power consumption, like rotary vane types, can lead to significantly higher energy bills over time if they spend much time idling. In contrast, compressors with lower idle power usage, like reciprocating models, are more energy-efficient in such conditions. Understanding this helps in selecting the right compressor for the application and optimizing system performance to reduce energy waste and operational costs. Compressors motors should use at least be IE3/Premium grade class.

3.2.1.1 *Lubricated screw compressors*

Rotary-screw compressors use two tight meshing spiral rotors to compress the gas. Lubricating oil bridges the space between the rotors, both providing a hydraulic seal and transferring mechanical energy between the rotors, allowing one rotor to be entirely driven by the other.

The effectiveness of this mechanism is dependent on precisely fitting clearances between the spiral rotors and between the rotors and the chamber for sealing of the compression cavities. However, some leakage is inevitable, and high rotational speeds must be used to minimize the ratio of leakage flow rate over effective flow rate.

The idling power consumption for this type is rather high, and idling time forced to be rather long to avoid overheating the motor with too many starts when modulating. This also calls for a larger buffer tank if pressure must be kept within reasonable limits.

This type of compressor is by far the most common for industrial applications. Sizes range from small workshop air compressors to 8,400 kW heavy industrial compressors with output pressures as high as 60 bar.

3.2.1.2 *Oil-free screw compressors*

This type works basically as the lubricated type, except that in an oil-free compressor, the air is compressed entirely through the action of the screws, without the assistance of an oil seal. In addition, timing gears ensure that the male and female rotors maintain precise alignment without contact which would produce rapid wear

Oil-free usually have lower maximal discharge pressure capability as a result and are typically also more expensive. However, multi-stage oil-free compressors, where the air is compressed by several sets of screws, can achieve pressures of over 10 bar and output volume of over 60 m^3/min.

Oil-free compressors are used in applications where entrained oil carry-over is not acceptable, such as pharmaceutical- and semiconductor manufacturing. However, this does not preclude the need for filtration, as hydrocarbons and other contaminants ingested from the ambient air must also be removed prior to the point of use. Consequently, air treatment identical to that used for an oil-flooded screw compressor is frequently required to ensure quality compressed air.

3.2.1.3 *Reciprocating compressors*

With one or more pistons coupled via connecting rod(s) to a crankshaft this is one of the oldest types of compressors, and it used to be the most common type. Today it is mostly used for smaller applications and often coupled in two stages for low and high pressure. The main advantage is a low idling consumption and low-cost investment. Disadvantages are more moving parts, usually no oil-free versions, vibration and noise.

3.2.1.4 *Vane compressors*

Rotary vane compressors are a type of positive displacement compressor that is used in a wide range of industries. It has a simple design, low cost, reliable operation and rather low noise level. A main drawback is that it is not as efficient as other compressor types, and the sliding vanes can wear out over time, requiring maintenance. Some models require oil lubrication, which can be a disadvantage in certain applications.

3.2.1.5 *Rotary lobe compressors (Roots)*

These positive displacement types are often used in applications with high flow and low pressure. A good quality Roots compressor (or equal type) can be a good alternative to a screw- or reciprocating compressor that are forced to operate at low pressure. Rotary lobe compressors are also reliable because of simple design.

4 Improving energy efficiency in compressed air system

Electricity consumption from compressed air systems can represent a substantial share of a factory's total energy use, as compressed air is often utilized for a wide range of applications across production processes. However, air compressors are very inefficient, making it highly beneficial to reduce compressed air requirements and, where possible, replace compressed air powered equipment with more energy-efficient alternatives. Based on results of previous pilot studies conducted by UNIDO in China [6] and more recent projects carried out at Indonesian enterprises, as described in section 6 of this guideline, energy saving projects in compressed air systems will have typical payback times of 1,5-3,0 years.

4.1 Eliminate use of compressed air

The most effective way to reduce energy consumption in a compressed air system is to eliminate its use where possible by implementing alternative technologies and thereby reducing system size requirements or potentially removing the need for a compressed air system altogether. Compressed air should only be used if safety enhancements, significant productivity gains, or labour reductions are obtained.

If end users make use of compressed air the equipment should be designed with as low pressure and air flow demand as possible.

4.1.1 *Inappropriate users of compressed air*

Compressed air can be used for a wide range of applications. However, for many of these applications a more energy efficient solution exists. Table 4 lists a wide range of end users where a more energy efficient solution exists.

Table 4: Overview of potential inappropriate uses and suggested alternatives [1][

Potentially inappropriate uses	Suggested alternatives/actions
Clean-up, Drying, Process cooling	Low-pressure blowers, electric fans, brooms, nozzles
Sparging	Low-pressure blowers and mixers
Aspirating	Atomizing Low-pressure blowers
Padding	Low to medium-pressure blowers
Vacuum generator / ejector pump	Dedicated vacuum pump or central vacuum system
Personnel cooling	Electric fans
Open-tube, compressed air-operated vortex coolers without thermostats	Air-to-air heat exchanger or air conditioner, add thermostats to vortex cooler
Air motor-driven mixer	Electric motor-driven mixer
Air-operated diaphragm pumps	Electric motor driven diaphragm pump

Pneumatics valves	Electric or hydraulic driven valves
Hand tools	Electric tools
Idle equipment*	Put an air-stop valve at the compressed air inlet
Abandoned equipment**	Disconnect air supply to equipment

2].

* Equipment that is temporarily not in use during the production cycle.
** Equipment that is no longer in use either due to a process change or malfunction.

4.1.2 *High flow/low pressure is not a fit for compressed air*

Air compressors are not suited for applications where the need is high air flow with low pressure. If the required pressure for the end user is below the air compressors lower limit, it will not be able to deliver the demanded air flow. This is solved by increasing the system pressure and hereby the energy consumption. This case can be solved with using alternatives solution as presented in Table 5 .

Table 5: Alternative solutions to low-pressure end uses [1].

Existing low-pressure end use	Potential alternatives	Reasoning
Open blowing	Fans, blower, mixers, nozzles	Open-blowing applications waste compressed air. For existing open-blowing applications, high efficiency nozzles could be applied, or if high-pressure air isn't needed, consider a blower or a fan. Mechanical methods of mixing typically use less energy than compressed air.
Personnel cooling	Fans, air conditioning	Using compressed air for personnel cooling is not only expensive but can also be hazardous. Additional fans or an HVAC upgrade should be considered instead.
Parts cleaning	Brushes, blowers, vacuum pumps	Low-pressure blowers, electric fans, brooms, and high efficiency nozzles are more efficient for parts cleaning than using compressed air to accomplish such tasks.
Air motors and air pumps	Electric motors, mechanical pumps	The tasks performed by air motors can usually be done more efficiently by an electric motor except in hazardous environments. Similarly, mechanical pumps are more efficient than air-operated double diaphragm pumps. However, in an explosive atmosphere and/or the pumping of abrasive slurries, the application of a double diaphragm pump with appropriate pressure regulating and air shut-off controls may be appropriate

4.2 Reduce pressure level and air flow

If compressed air cannot be avoided, it is evident to investigate whether it is possible to reduce the system pressure and air flow. Reducing the system pressure introduces large energy savings as reducing the system pressure with 1 bar reduces the energy consumption by the compressors by 8% [2].

4.2.1 *Investigate required pressure level*

The discharge pressure from the compressor is typically set too high to ensure that all end users have the necessary pressure. However, this results in unnecessary energy use from the compressor. A good indication if the pressure level is set to high is the use of pressure reducing valves. If many reducing valves are used in the distribution system, it indicates that the pressure level is too high.

The discharge pressure should be set by the user furthest away or the user with highest demand. Table 6 lists typically pressure demands for different applications.

Table 6: Recommended maximum pressure for a range of applications [2].

Equipment	Pressure demand [bar(a)]
Blower	0.5-1.0
Transport	2.0-4.0
Cleaning (air guns)	2.0-3.0
Pneumatic actuators	4.0-6.0
Tool for assembly (Pneumatic)	6.0-6.5
Processing tools (Pneumatic)	6.0-6.5
Process machines	Machine depended.

As shown by Table 6 most equipment can operate at absolute pressure of 5 bar or lower. Pneumatic tools can operate at lower pressures, but it will affect their efficiency. Often the system pressure is dictated by a few applications and substituting these with a more efficient alternative should always be considered.
In general, it is rare to have a system pressure above gauge pressure of 7 bar . If this is the case and no end user requires this pressure level it could indicate that the pressure loss in the system is too high.
Gauge pressure (bar(g)) measures pressure above the surrounding air pressure. Absolute pressure (bar(a)) measures from a total vacuum, so it includes atmospheric pressure. At sea level, absolute pressure is about 1 bar higher than gauge pressure. So, 6 bar(a) is the same as 5 bar(g).

To get the best overview of the compressed air system a mapping of demands regarding air flow and pressure must be performed for all users. For further information see section 5.1.

Alternatively, it is proposed to try to incrementally reduce the system pressure while monitoring if the equipment's operation is affected. This approach does not require any investment but will immediately show the potential to lower the pressure and save energy.

4.2.2 *Install buffer capacity*

Buffer tanks placed close to end users with sudden high demands are a good alternative to extra compressor capacity and/or increased system pressure.
Buffer tanks placed in the compressor central are usually not serving the same purpose but instead designed to even out the pressure fluctuations that can occur when individual compressors start and stop. This is also necessary when having a VSD-compressor as this can only regulate down to 30% flow before on/off operation is necessary, see section 4.3.1 for more information.
It is always important that piping to and especially from buffer tanks have a large dimension with a minimum pressure loss at sudden peak high airflow.

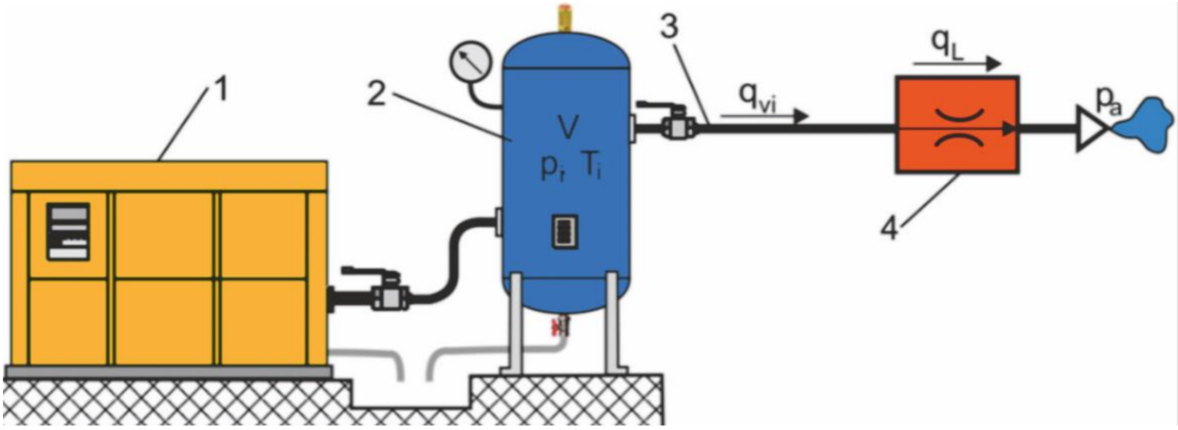


Figure 10 : Diagram of compressed air system: 1-compressor, 2-buffer tank at stable pressure pi and temperature Ti, 3-pipeline with air at flow qi, 4-symbolic of the leak point with air flow leakage qL that releases air at atmospheric pressure pa.

Figure 10 shows the design of the buffer tank installation. The size of the buffer tank in the central should be 6-10 times bigger in m^3 than the air input flow to the compressor in m^3/s.
Example: if the compressed air flow demand is 0.12 m^3/s the buffer tank should be between 0.7 and 1.2 m^3 as a minimum

4.2.3 *If multiple pressure levels are needed, it should be split into separate systems*

If the compressed air need is high at different pressure levels it can be profitable to make separate systems. If there is a demand for compressed air at both 6–7 bar and 2–4 bar, it should be evaluated whether separating the system and using multiple compressors operating at different pressure levels is a more energy-efficient and cost-effective solution.
In this scenario it is important to address whether the saving in operating at a lower pressure can compensate for the investment in new compressors, new distribution system etc.

4.2.4 *Shut off supply when process is idling.*

If certain machines or sections of the compressed air distribution system are frequently idle, it can be beneficial to install automatic shut-off valves. These valves can isolate unused areas of the system during non-operational periods, preventing unnecessary compressed air supply. This helps reduce energy waste and minimizes losses due to leaks in idle sections, ultimately improving overall system efficiency and lowering operational costs.

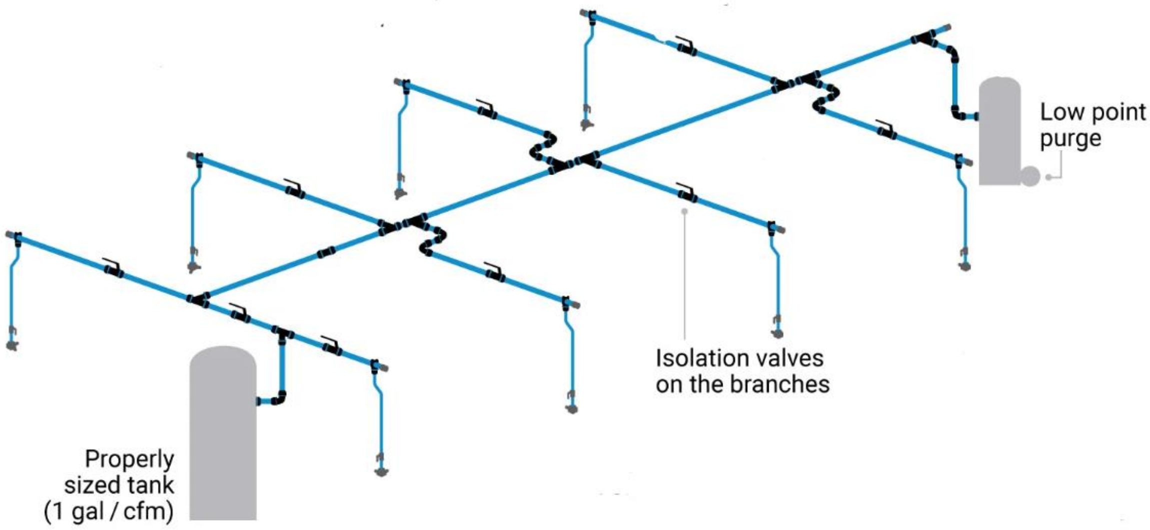


Figure 11: Schematic of a compressed air distribution system equipped with shut-off valves. These valves allow isolation of idle sections or machines, preventing unnecessary air supply and reducing energy losses from leaks during non-operational periods.

4.2.5 *Use pressure reducing valves*

If the system pressure is as low as possible but there still is a larger difference to the user with the lowest pressure demand, pressure reducing valves should be installed at this user. This will reduce the loss from leakages, which increases with a higher pressure. Furthermore, the air flow can be adapted to the specific need and the machines are protected.
The disadvantage is that a pressure loss is introduced, and the energy efficiency is therefore reduced. Due to this pressure reducing valves should be limited in a system. In terms of illustration, Figure 11 can substitute shut-off valves with pressure reducing valves: instead of shutting off the pressure in certain periods, simply adjusting if certain sections of distribution systems require lower pressures than others.

4.3 Energy efficient control of air compressors

Air compressors are most efficient when operating at full load. However, with a varying need at the end users there are several control strategies to use, to maximize the efficiency of the plant.
This catalogue covers three control strategies for single compressors:

ON/OFF: The compressor run at full load until the system pressure reaches its upper limit, where after the compressor is turned off. When the system pressure reaches its lower limit, the compressor turns on again increasing the pressure up to the upper limit. Reciprocating compressors have this opportunity. Figure 12 shows a visual chart of this condition.

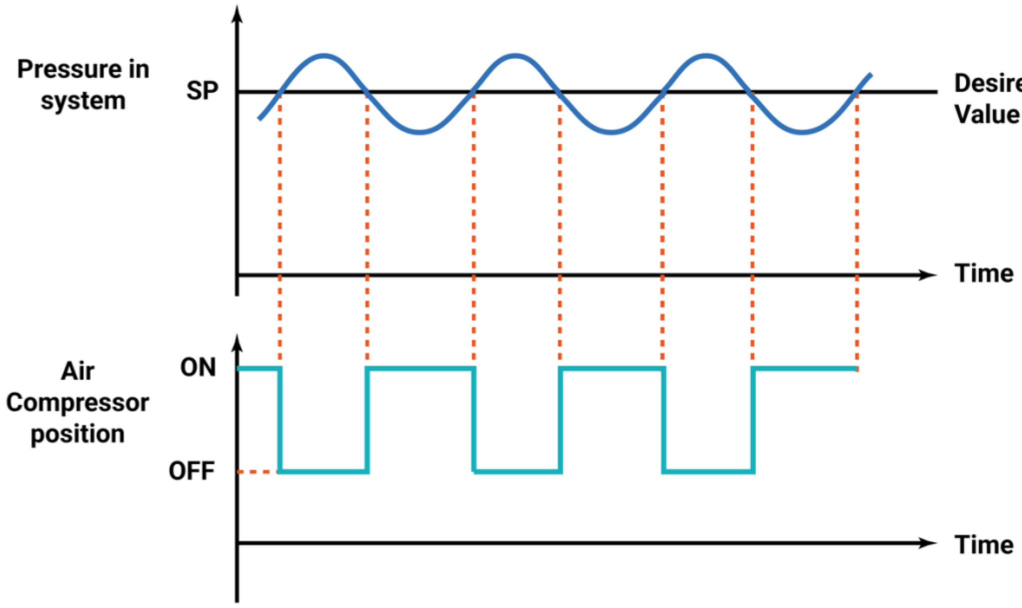


Figure 12: visual diagram of the control system is needed to illustrate the conditions of on/off and full load, replacing ON OFF with 30% of full load

Full load/unload: The compressor run at full load until the system pressure reaches its upper limit, where after the compressor goes into unload condition where it consumes 30% of the full load energy consumption. If the system pressure reaches the lower limit the compressor goes from unload to full load until the upper limit is reached. If the unload condition is withheld for a longer period, the compressor shuts off. Reciprocating compressors does not have this opportunity, but screw compressors have.

Variable speed drive (VSD): By changing the rotational speed of the compressor, it can keep the pressure constant but with varying air flow. With this method the air flow can be regulated down to 30% of maximum. Hereafter the compressor will work as ON/OFF and in this case a buffer tank can help the performance, see section 4.2.2. The benefit is highest when the flow is in the range 30%-70% of maximum flow.

4.3.1 *Control compressors to have best efficiency at the longest average operational time.*

Controlling the combination of compressors to meet a given demand must be done in a way that results in an all-round best efficiency at the longest average operational time.

4.3.1.1 *Recommended strategy with constant flow*

If the demand is rather constant there is no other need than an ON/OFF regulation or a compressor running at Full load/unload. If small fluctuations occur, this must be solved by installing a buffer tank as described in section 4.2.2.

The control strategy depends on how many starts and stops the compressor is going to have, as the motor manufacturer has a limit for how many starts and stops the motor can have during an hour. A Full load/Unload strategy can therefore be necessary.

4.3.1.2 *Recommended strategy with varying flow*

If the flow demand has a large variation, the most efficient solution is achieved with a combination of compressors. The main recommendation is to have a setup with a main compressor with VSD and then a secondary or more compressors operating ON/OFF in cascade. The cascaded (non-VSD) compressors can be selected to be of different sizes, e.g.: 1 and 2 times the dynamic capacity of the main compressor. The VSD compressor should always be the first to start and the last the stop. The main idea is to operate all involved compressors at their optimum efficiency load as long as possible. This is typically achieved by using a so-called intelligent controller.

VSD compressors cannot regulate the flow down to 0%. The first (non-VSD-) compressor in the cascade should have the same capacity as the actual dynamic load range of main (VSD-) compressor, typically from 35% to 100% of full load, resulting in the size 65% of the VSD compressor. If redundancy is required, it should be the main VSD compressor that is duplicated, and all the following cascaded compressors should of equal size (65%)

Example for efficient control strategy
Figure 13: illustrates how multiple compressors should be controlled based on the demand. Here it is shown how the compressors are turned on one by one and that the compressor with VSD regulating in between for highest efficiency.

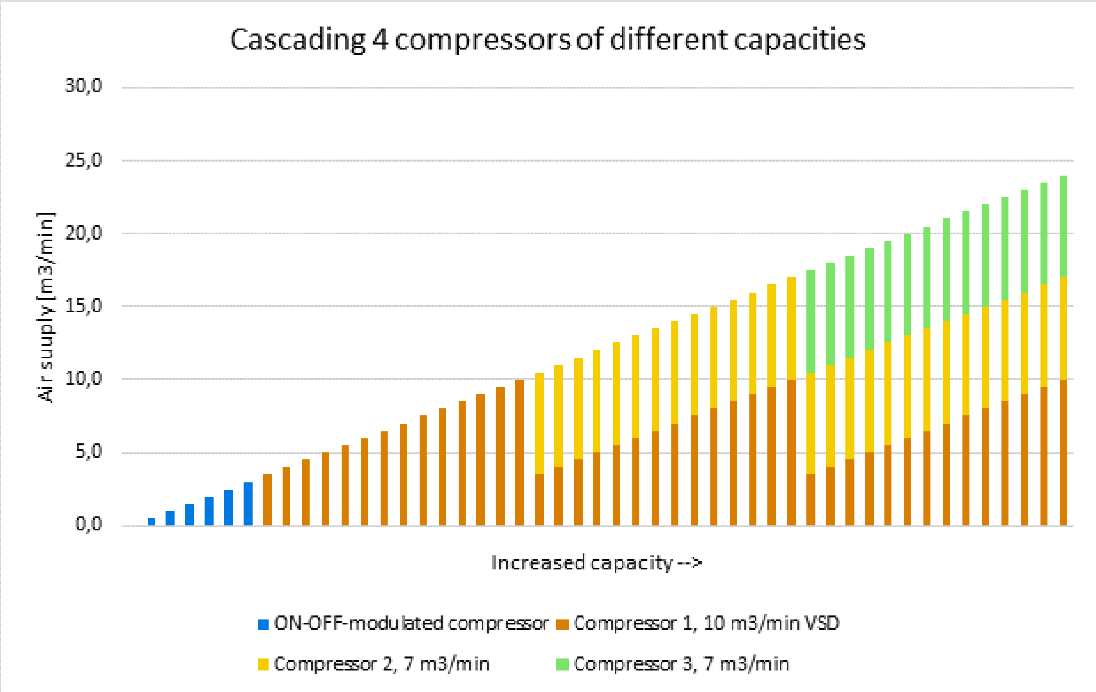


Figure 13 : Illustration of how a cascading control system should run.

In Figure 13 t he ON-OFF modulated compressor can deliver varying flow rates due to an installed buffer capacity in the compressor central.

4.4 Utilize excess heat from the compressors for other purposes

As mentioned, compressed air is one of the most in-efficient unit operations in the industry since only a fraction of the energy input end up in the compressed air, while the rest is converted to heat. However, a large part of this heat can be recovered.

The heat can be collected either by air or by water. Using a water-borne system, Table 7 shows the possible percentage of recoverable heat , and furthermore shows the achievable temperature based on compressor type

Table 7: Specifications regarding recoverable heat from air compressors.

Compressor type	Recoverable heat	Media	Achievable temperature
Oil free compressor	75-80%	Water	90°C
Oil compressor	75-80%	Water	75°C

The recovery of heat will not improve the energy efficiency of the compressed air system, but it can help reduce other energy inputs e.g. fossil fuels used for space heating.
Using air to recover the heat will result in a low efficiency compared to using water. If air is used it should only be used for room heating close to the compressor or else the benefit will decrease significantly. If the heat cannot be utilized externally it can be used internally by an adsorption-type air dryer if present.
To enable heat recovery, compressors must be equipped with a dedicated heat recovery module. If this module is not installed from the outset, it can often be retrofitted into the existing compressor system. New compressors should always be bought prepared for heat recovery. When designing new installations or factories that utilize compressed air, integrating a heat recovery system into the initial design allows for effective reuse of waste heat from compressors and thereby reducing the need for additional heating during operation.

Since the water heated by excess heat from the excess air from the air compression process will function as a cooling medium for either cooling the air itself or the oil in the compressor, the compressor manufacturer will usually specify a maximum outlet water temperature, usually in the range of 75 to 90°C. Depending on the heat exchanger design, this return temperature should be around 30°C max. 50°C.

Depending on the pressure of the compressed air, considerations should also be made regarding the heat exchanger design, which can be a plate heat exchanger for pressure below 8 bar, and shell-and-tube heat exchangers for pressure above 8 bar.

4.5 Treatment of compressed air helps maintaining system performance

When an air compressor draws in ambient air, it does not only take in clean air but also any contaminants present in the surrounding environment—such as dust, oil vapours, and moisture. Unless the compressed air undergoes adequate treatment (using filters and dryers), these contaminants will remain present and will be delivered throughout the entire compressed air distribution system. This can lead to problems like equipment malfunction, product contamination, and increased maintenance.

For example, in a food processing plant located in a humid and dusty area, compressed air is used during the packaging stage. Because the facility did not install appropriate filtration and drying systems, moisture and dust from the ambient air were introduced into the compressed air supply. Over time, condensation formed within the distribution lines, and dust particles entered the packaging equipment. As a result, several batches of food products became contaminated, causing product recalls and requiring costly maintenance to clean the pneumatic systems. This situation highlights the importance of treating compressed air properly, especially in environments where air purity is critical to product quality and safety.

4.5.1 *Use filters to remove contamination from the compressed air*

On the inlet to the compressor and on the outlet from it a filter should be installed to remove contamination in the air to protect the compressor and the end-users downstream from it.
Filters uses energy in terms of the introduced pressure loss in the system. The chosen filtration level should therefore not be higher than requirement from applications. Furthermore, the filters should be checked regularly to ensure minimum pressure loss during operation.
For every 0.2 bar the pressure loss increases across at the suction path due to choked filters, the compressor power consumption increases by about 2% for the same output [4].

4.5.2 *Cool the air before further treatment*

As the air is compressed the temperature of the air increases up to 150°C. To protect the downstream components the air should always be cooled in an after-cooler because if humid hot air is sent into the buffer tank it causes more condensation in the buffer tank and distribution lines. The consequence of this is increased corrosion, pressure drop and leaks in piping and end-use equipment.
It is therefore important that the after-cooler is properly maintained to ensure adequate cooling and ensuring the desired performance.

4.5.3 Avoid Over-Drying

The compressed air needs to be dried to prevent stoppage and damages which can be caused by water in the system. It is especially important to dry the air if the pipework is outdoors due to the risk of frost. There are two common application for drying the air: cooling dryer and a des iccant dryer. The cooling dryer is the most common and the one with the lowest energy use.

Table 8: Different drying methods and their achievable dew point and specific energy use [3].

Drying method	Pressure dewpoint	Specific energy use*
Cooling dryer	+3°C	0.1 kW/(m3/min)
Heat regenerative desiccant dryer	-40°C	0.5-0.6 kW/(m3/min)
Heatless regenerative desiccant dryer	-20°C -70°C	1.4-1.6 kW/(m3/min)

*As per ISO 7153 Option A: Reference point 1 bar (abs), 20°C

"ISO 7153 Option A" refers specifically to the reference ambient conditions used for standardized measurements and comparisons in relation to air treatment equipment or testing. In documents such as technical data sheets for compressed air dryers, "Equivalent to ISO 7153, Option A: Reference point 1 bar(abs), 20 °C" means that equipment performance data—such as capacity or purge air volume—is measured or specified at an absolute pressure of 1 bar (atmospheric pressure) and a temperature of 20 °C.

As shown in Table *8* the cooling dryer is the one with lowest energy use and should therefore always be used if it can meet the required dry level. If the demand is higher than the ability of the cooling dryer, the heat regenerative desiccant dryer should be used. To optimize the energy use for the heat regenerative desiccant dryer, recovered heat from the air compressor could be utilized for this process. *Table 9* shows the recommended dryer for various users.

Table 9: Recommended dryer technology based on end use [2].

User	Dewpoint demand	Recommended dryer
Cleaning	Low	None
Tool for assembly	Low	Cooling dryer
Processing tools	Low	Cooling dryer
Process machines	Machine specific	Cooling dryer / desiccant dryer
Outdoor piping	High	Cooling dryer / desiccant dryer

If the demand requires a desiccant dryer always make use of a cooling dryer beforehand to reduce the overall energy load from drying the air.

Besides the dew point level and energy use, one should also be aware of the pressure loss. It is recommended that the pressure loss should be less than **0.15 bar** [1] at the furthest point of use.

4.6 Create maintenance scheme for keeping an energy efficient system

A maintenance scheme is necessary to ensure the performance and maintain an efficient system. This does also apply for the equipment using compressed air. The following indicates a poor efficient operation and maintenance:

- Bad air quality – i.e oil content ≤ 0.1 mg/m³ and pressure dew point ≤ -40°C (for Class 2 humidity) according to ISO 8573-1:2010
- Too small air flows to the equipment and processes – flow rates below 90% of design specifications.
- Too large pressure loss – pressure drops exceeding 0.5 bar between the compressor and the point of use
- Too large losses from leaks – total leakage accounting for more than 10% of total compressed air consumption

Furthermore, a too high energy consumption typically indicates that the compressed air system does not operate efficient and if nothing is changed it can lead to stoppage. Good maintenance also prolongs the lifetime of the equipment.

For the compressor the following should be checked minimum one time a year or what is stated from the manufacturer [9] (shall always be checked in the manual of the actual compressor):

- The compressor should be lubricated based on the manufacturer's specification. Too much lubrication can be as harmful as too little.
- As the compressor and motor dissipates heat it is important to keep all the air passages clean and free of obstructions. If the compressor and motor is enclosed, it is vital that cooling fines are kept free of debris. Inefficient cooling of the compressor and motor can shorten the lifetime and increase energy consumption.
- If the motor uses belts these should be checked regularly as too loose a belt wastes energy but a too tight one can led to excessive bearing wear. Therefore, follow the manufacturers recommended requirements. However, if possible, avoid using belts, as it increases energy loss.

4.6.1 *Regularly check for air leaks*

Air leaks can be a large energy consumer if not fixed. It is commonly seen that about **25-30%** [10]of the produced air is due to leaks. Leaks can occur in many places. Below shows common locations where leaks occur.

- Couplings
- Tubes and pipes
- Open condensate traps
- Pipe seals
- O-rings in bad condition
- Hoses
- Pressure regulators
- Valves
- Quick connectors
- Storage tank drains

Table 10 indicates the needed compressor work needed to compensate for leaks of varying sizes.

Table 10: Necessary work from compressor to compensate for air leakage based on pressure and hole diameter [2].

Size of hole	Pressure at 4 bar(g)		Pressure at 8 bar(g)	
	Flow [l/s]	Energy [kW]	Flow [l/s]	Energy [kW]
1 mm	0.7	0.2	1.3	0.5
5 mm	18	4,6	33	13
10 mm	73	18	132	50

When the production plant is not in operation, the total leakage loss can be measured directly. During operation, leaks can be detected relatively easily and accurately using ultrasonic measuring equipment developed for the task. The appropriate inspection frequency is difficult to define universally, as it depends on system-specific conditions. In some instances, monthly inspections may be warranted, while in others, a semi-annual interval may suffice. It is recommended that the inspection frequency be adjusted based on the volume of leaks detected. Through ongoing leak management programs, it is possible to reduce leak losses to **10–15%** **[10]**.

4.7 Monitor and manage compressed air energy consumption

Besides the general maintenance it can be hard to tell when the performance of the compressed air system is decreasing. It is therefore recommended to establish KPI's describing the performance. The KPI should describe how much energy is used to produce the compressed air and how much air is used in production.

For air compressors an example of instrumentation for KPI monitoring is illustrated in
Figure 14: .

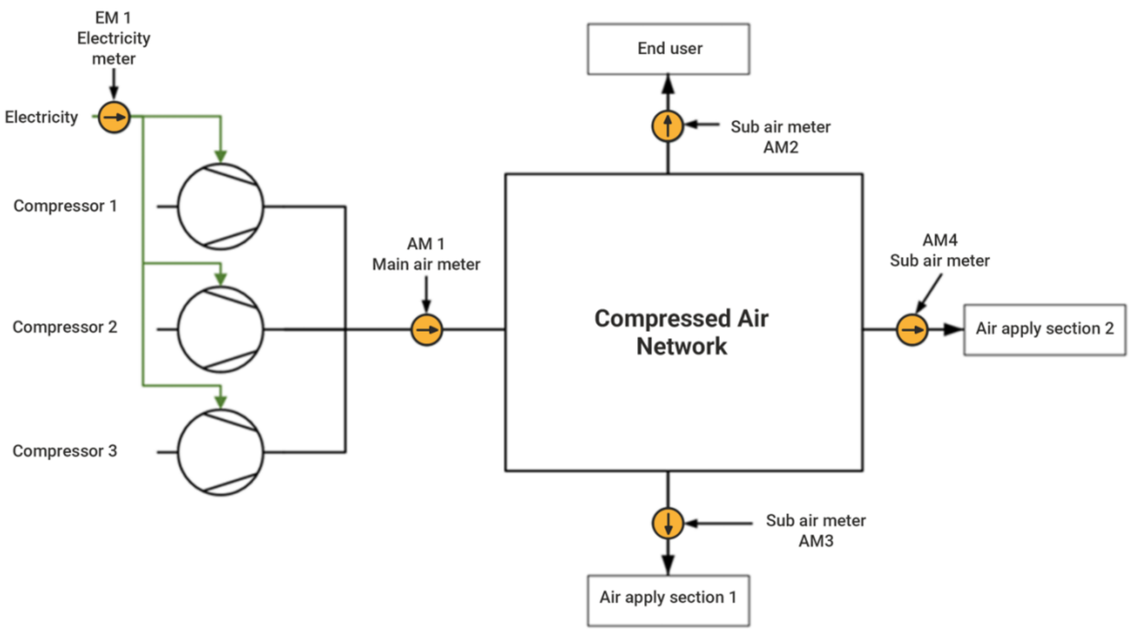


Figure 14 : Example of meters to monitor air consumption.

By installing air meters strategic places, like in
Figure 14: , it is possible to locate where the air is used, which can help locate any air leaks.

4.7.1 *Set up the right Key Performance Indicators (KPIs)*

Setting up KPIs for the compressed air system can help monitor the performance of the system. The established KPIs should be examined minimum every month. Table 11 lists recommended KPIs for a compressed air system.

Table 11: Recommended KPIs for a compressed air system.

KPI	Calculation	Goal
Loaded operating hours	Loaded hours / operation hours	Monitor if the compressors have many unloaded hours
Pressure loss in air treatment	Outlet compressor pressure – Pressure in buffer storage	Monitor the pressure loss from filters, dryers etc. helps indicating when filters need to be changed, dryers cleaned etc.
Pressure loss in distribution system	Pressure in buffer storage – Pressure in the system	Monitor efficiency in the distribution system

Specific energy use	Electricity consumption / air production	Monitor the system efficiency.
Air use per production	m^3 / ton product	Monitor the efficiency at the end user.
Air use per supply area	m^3 / area	Monitor the air usage for specific areas in production. Can help detect air leaks.

For the KPIs listed it is recommended, as a minimum, to monitor the specific energy use for the compressed air system over time. Monitoring the specific energy use over time, preferable automatically, will cover the other KPIs as well except product related KPIs. The recommended KPI's are general for all compressed air systems, with the exception of m^3 per ton of product or per area. These KPI's must be defined more specifically for each individual plant.

The specific energy use will vary depending on the pressure demand in the system. Figure 15: shows where the specific energy use should be depending on the system pressure.

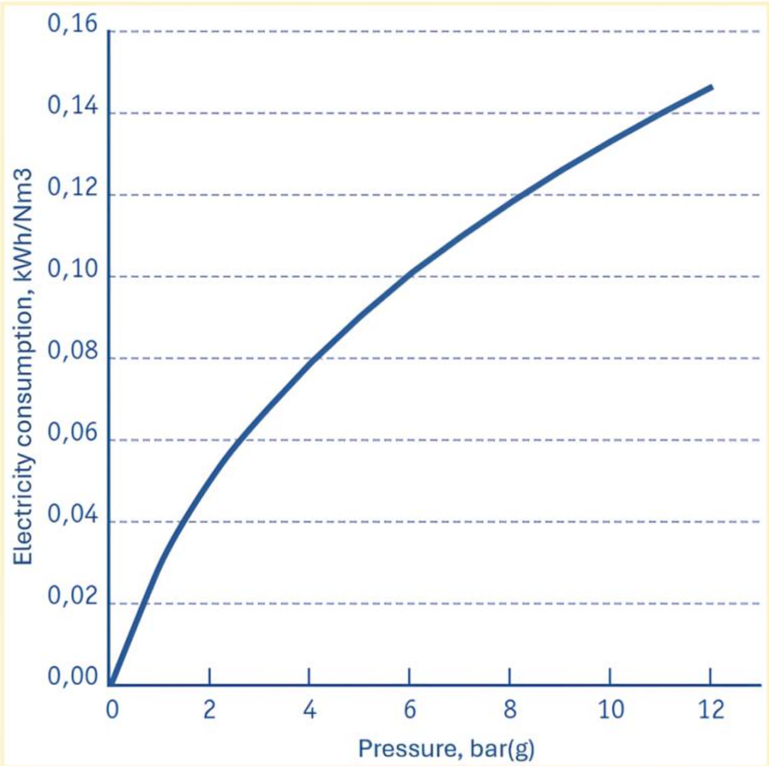


Figure 15 : The recommended specific energy use for compressed air at different pressures [5].

4.7.2 *Monitor the KPIs on a regularly basis*

When the KPIs are established, they should be a part of the regular monitoring of the production. Doing so will help identify any malfunctions in the system quicker and help maintaining the same performance and energy efficiency of the system.
Furthermore, total electricity consumption and produced airflow, pressure, humidity and temperature must be monitored and logged for the compressor central.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5 Selection and Specification of New Compressed Air Installations

5.1 Optimize operational demand before design

To ensure an efficient compressed air system, it is essential to start by analyzing the demand. The most effective way to optimize such a system is often to avoid using compressed air altogether. Therefore, when designing or dimensioning a compressed air system, the first step should be to assess the end users. Can the end users avoid using compressed air by switching to alternative solutions?
Section 4.1 provides a range of alternatives to compressed air for various processes.

5.1.1 *Perform a demand analysis*

To have an energy efficient compressed air system a thorough demand analysis including an evaluation of the necessity for every single demand, must be carried out. For each end user, the air flow and pressure level must be known. Lastly the demand analysis should consist of data showing standby, average and peak flow demands at operational system pressure.
Figure 16 shows a workflow on how a demand analysis of compressed air demand can be completed.

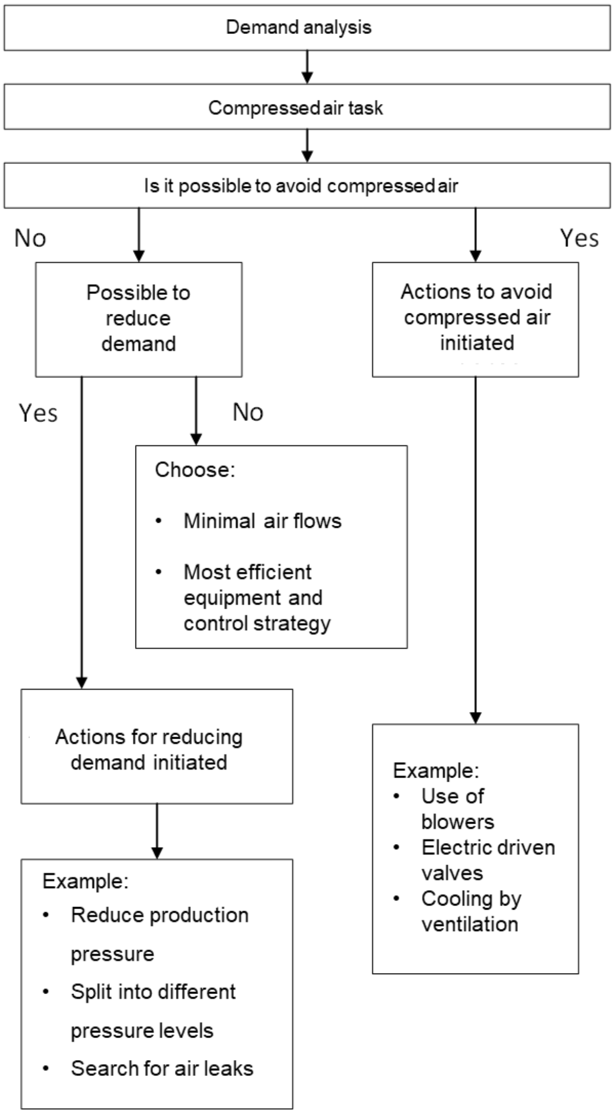

Figure 16 : Workflow for a demand analysis of a compressed air system [2].

Depending on the process there could also be demands regarding low water content, a specific temperature and/or purity.

5.1.2 *After demand analysis, create a mapping of the system*

After the demand analysis has been performed the mapping of the system should be created. This helps understanding where the demand is high, and special attention must be made to the design of the system. This mapping should also help designing the compressor central and distribution net. In the mapping for every user the following data must be known:

- Peak flow and typical duration
- Average flow and concurrency
- Idle flow, if any
- Pressure demand
- Water content
- Particle content
- Temperature
- Piping distance from compressor central to consumers.

5.1.3 *Relevant tools*

The U.S. Department of Energy have made a tool where it is possible to model one's system and find energy savings potentials. The tool does also cover compressed air, meaning that it is possible to model your own system together with the end user.

With the tool it is possible to calculate savings within energy, economic and CO_2-emissions. The tool can be found here: https://measur.ornl.gov/landing-screen

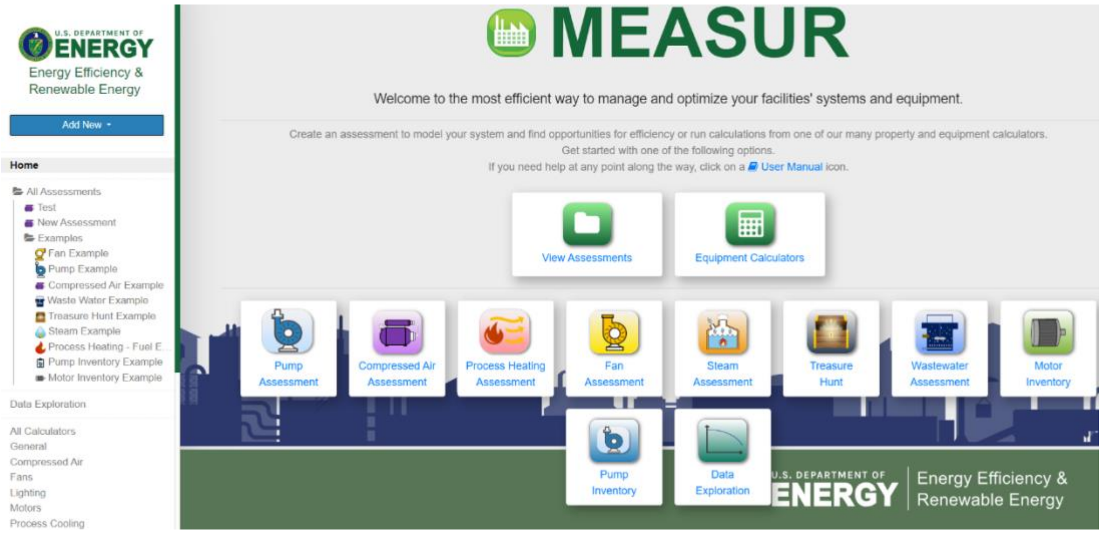

Figure 17 : Tool made by USA's Department of Energy to investigate energy efficiency within different utilities.

5.2 Optimize system design to reduce consumption

Besides reducing the demand for compressed air flow and pressure, a well-designed central and distribution system is equally important for providing energy efficient compressed air.

5.2.1 *Central layout*

The compressor central should be placed in a central location as referenced to the users, in order to make distribution piping as short as possible. Compressors can be noisy and result in vibrations, which must also be considered when choosing the location and designing the machine room containing the compressors.

5.2.1.1 *Ensure proper ventilation and cooling*

The compressor room must be well ventilated, even if heat recovery is established. Make sure that any hot exhaust air from one compressor is not blown directly into the intake of another compressor. The reason is that the compressor power consumption increases when the intake air is getting warmer (approx. 3.5% per 10°C). Excess temperatures can also cause compressor, cooler and dryer shutdown. Temperatures at the air intake should never exceed **35°C**. In some cases, air conditioning with cooling will be necessary.

5.2.1.2 *Avoid a cramped compressor room*

The compressor room must not be so small that piping between all the different components gets crammed, with excess use of narrow pipe dimensions, sharp bends and T-fittings. All cut-off-valves should be of ball type with minimal pressure drop when fully opened. The distance between compressors and other equipment, and to the walls surrounding, must never be less than 1.0 meter, to ensure proper space for service of all equipment.

5.2.1.3 *Monitoring the central*

As a minimum, total electricity consumption and produced airflow, -pressure, -humidity and -temperature, must be monitored and logged for the compressor central as described in section 4.7. Air-flow measuring must be done in a non-obtrusive way in order to keep pressure drop low.

An intelligent monitoring system can be an effective key to preventive maintenance of compressor central, and a mean to keep off leaks and sudden unusual consumptions.

5.2.2 *Compressor configuration and control*

A larger compressor central is often best designed using one main compressor with variable speed drive (VSD), combined with one or more non-VSD compressors that are started in cascade according to demand.

5.2.2.1 *Make use of intelligent control*

Controlling the combination of compressors to meet a given demand must be done in a way that results in an all-round best efficiency at the longest average operational time. This is sometimes best achieved with a combination of compressors where the cascaded (non-VSD) compressors are of different sizes, e.g.: 1 and 2 times the dynamic capacity of the main compressor. The main idea is to operate all involved compressors at their optimum efficiency load as long as possible. This is typically achieved by using a so-called intelligent controller. A simplified example of how multiple compressors are controlled to meet the demand can be seen in section 4.3.1.2.

5.2.2.2 *VSD compressor limitations*

VSD-compressors cannot regulate the flow down to 0%. The first (non-VSD-) compressor in the cascade should have the same capacity as the actual dynamic load range of main (VSD-) compressor, typically from 35% to 100% of full load, resulting in the size 65% of the VSD-compressor. If redundancy is required, it should be the main VSD-compressor that is duplicated, and all the following cascaded compressors should of equal size (65%).

5.2.3 *Distribution and buffering*

5.2.3.1 *Piping*

Selected pipe dimensions must be so large that pressure drop from compressor central to user point never exceeds **0.2 Bar.** If this is not possible for large flow peaks (e.g.: Inrush-flows in tanks or large-volume actuators), local buffer tanks must be provided. Note that sometimes a large dimension piping can be enough to provide a necessary buffer). In general air velocity in the main piping and on the branches must not exceed **6.0 m/s.**

Any bayonet couplings or flexible tube connections must be of high quality with a documented life-time leak-rate.

Piping must be with no sharp bends and very few T-fittings. All cut-off-valves should be of ball type with minimal pressure drop when fully opened.

5.2.3.2 *Sectioning and topography*

If possible, the main distribution pipe should be arranged in a circle, and in this way some redundancy can be achieved together with reduced pressure losses. To every user point on the circle, air can flow from two directions.

If sections of the distribution grid are prone to leaks and in periods not in use, it can be beneficial to install automatic cut-off valves for these sections.

5.2.3.3 *Local buffer tanks*

As also described in section 4.2.2 buffer tanks can help optimize the compressed air system when it comes to operating the compressors.
A buffer tank close to end users with sudden high demands can be an alternative to an extra compressor capacity or increased system pressure.
Buffer tanks in the central helps by even out the pressure fluctuations that can occur when individual compressors start and stop. This is also necessary when having a VSD-compressor, as they cannot regulate down to zero-flow.

It is always important that piping to and especially from buffer tanks have a large dimension with a minimum pressure loss at sudden peak high air flow.

6 Examples from the energy auditing

Over the course of various energy audits and industrial energy management programs, several best practices have emerged. These range from basic maintenance measures—like fixing leaks or replacing filters—to more complex system-level optimizations such as variable speed drives (VSD), heat recovery systems, or pressure control using intelligent flow controllers (IFC).
The following 10 case studies were selected from real industrial sites across multiple sectors in Indonesia and Vietnam. Each intervention was chosen based on one or more of the following criteria:

- Energy savings potential
- Replicability across sectors
- Return on investment (payback time)
- Innovation or simplicity
- Impact on CO_2 emissions

By presenting these examples, the aim is to showcase not only the technical solutions but also their economic and environmental benefits, providing a practical reference for industry professionals, auditors, and policymakers. In Table 12 it is possible to see a summarized overview of the case studies presented in the section.

Table 12: Result overview and summary of the cases presented in the section.

Case	Title	Energy Savings [MWh/year]	CO_2 Reduction [t/year]	Cost Savings [M IDR/year]	Investment [M IDR]	Payback [years]
6.1	Pressure reduction via IFC	308	258	339	550	1.60
6.2	Compressor replacement with VSD	187	158	225	300	1.30
6.3	Leak fixing + solenoid valve	237	199	327	65	2.40
6.4	Centrifugal compressor replacing 4 screw units	1704	1431	1874	6000	3.20
6.5	Inlet air cooling	63	52	69	120	1.70
6.6	Exhaust air heat recovery	308	62	168	500	3.00
6.7	Heat recovery from piston compressor (35 bar)	911	184	504	1200	2.40
6.8	Heat recovery from screw compressor oil	403	339	443	1200	2.70
6.9	Clogged air filter replacement	122	—	146	90	0.60

6.1 Case 1) Reduction of the system pressure using intelligent AI flow controller

Industry: Consumer goods industry

Project summary: A consumer good company in Surabaya - East Java, Indonesia has installed intelligent flow controller (IFC) to reduce the system pressure at minimum requirement of the operating pressure of the compressor. The goal of the project is to reduce energy costs and greenhouse gas emissions.

Year of implementation: 2020

Status before implementation:
The installed pressure after air drier in the range of 69 - 95 psig (+/- 6 psig) was supplied to plant demand. The existing findings are listed as follows:

- Over supply of compressed air
- Lack of compressed air storage
- Uncontrolled end use of compressed air
- Improper control of air compressor
- Air compressors are operated to cater base demand and artificial demand to meet fluctuating demand

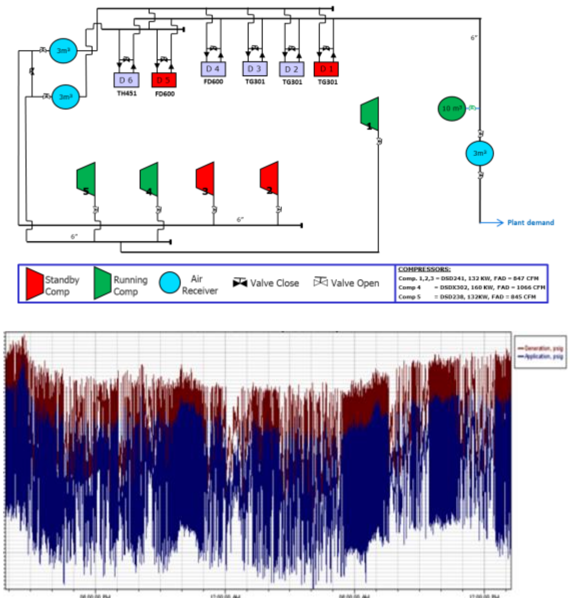

Figure 18 : Diagram of existing compressed air distribution at the factory and air supply & demand profile

When an air application is supplied with higher pressure than it needs, it will consume more air than it should. The additional air consumption is artificial demand.

Result:
In the project an intelligent flow controller (IFC) was installed, and it is working successfully. IFC creates usefull compressed air storage due to controlled differential pressure across upstream receiver & itself. This storage isolates compressors from demand side peaks & troughs. Peaks are met with stored compressed air instead of additional power.

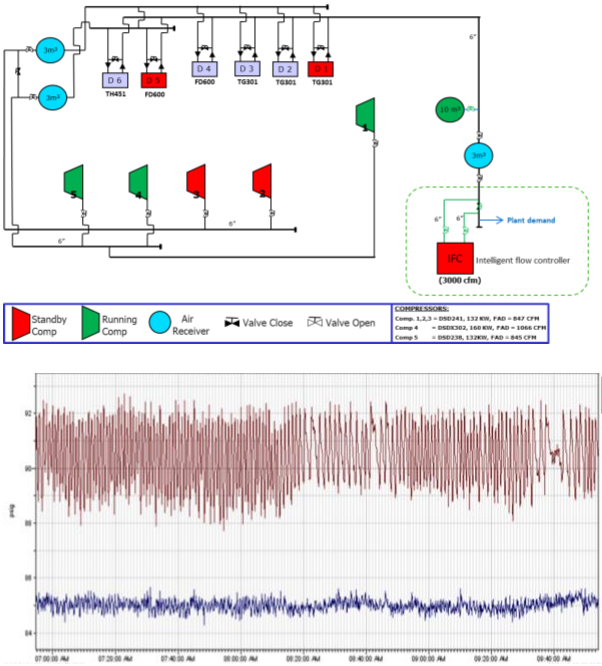

Figure 19 : Additional IFC and impact on air demand profile

The relative constant pressure after the air drier was achieved at 84 psig +/- 1 psig. Actual power saving of air compressor was reported at 8.6% total consumption or 308 MWh annually.

Results of the project	
Total investment costs	IDR 550 million
Energy saving	308 MWh/year
Cost saving	IDR 339 million/year
Payback time	1.6 year
GHG emission reduction	258 tons CO_2/year

6.2 Case 2) Install VSD air compressor to replace fixed speed air compressor

Industry: Consumer goods industry

Project summary: A consumer goods industry in Jakarta Province has successfully replace fixed speed with Variable Speed Drive (VSD) compressor. The goal of the project is to reduce power consumption of air compressor at variable load.

Year of implementation: 2024

Status before implementation:
The two existing units of fixed speed air compressor are operated with capacity of 75 kW. The average load of each compressor is operated at 75% and 57%. These compressors also simultaneously run at both load and no-load modes which cause a waste of electricity because the compressor does not produce compressed air but consumes a lot of electricity during such off-load time. Average power consumption was measured at 2,210 kWh/day.

Table 13: Daily Power Consumption of Compressors at Varying Load Levels w/o VSD

Comp.	Capacity, kW	Average load, % load-unload	Power consumption, kWh/day
Comp. A	75	75	1,185
Comp. B	75	57	1,025
Total power consumption			2,210

Result:
A new VSD air compressor with a capacity of 37 kW has been installed, to reduce the unload time of air compressors.

Table 14: Daily Power Consumption of Compressors at Varying Load Levels with VSD

Comp.	Capacity, kW	Average load, % load-unload	Power consumption, kWh/day
Comp. A	75	88	1,271
Comp. B	75	Off	-
Comp. C	37	90	386
Total power consumption			1,657

Figure 20 : A new VSD air compressor of 37 kW

After project implementation, the average power is 1,657 kWh/day or 187 MWh annually. Electricity saving rate equivalents to 25%.

Results of the project	
Total investment costs	IDR 300 million
Energy saving	187 MWh/ year
Cost saving	IDR 225 million/year
Payback time	1.3 years.
GHG emission reduction	158 tons CO_2/year

6.3 Case 3) Routine maintenance of the compressed air line such as the stoppage of air leakages

Industry: Powder milk enterprise

Project summary: In response to the energy efficiency program of group company international brand, a powder milk enterprise in Karawang – West Java, Indonesia, has implemented the project of pneumatic system improvement. The goal of the project is to reduce energy costs and greenhouse gas emissions.

Year of implementation: 2024

Status before implementation:
A remarkable amount of compressed air was leaked from 118 points of tubing joints and pneumatic actuators, thereby increasing the power consumption of the air compressor.

Figure 21 : Air leakage detection point in tubing and pneumatic actuator

In addition, the compressors operate continuously even during clean in place (CIP) without production time. The compressor room temperature remained quite high compared to the ambient temperature.

Figure 22 : Power consumption during CIP and normal production time

Result:
Several improvements have been made to the compressed air system such as:

- fixing compressed air leakage,
- installing electric control valve instead of pneumatic control valve for relatively constant load when new purchase

By improving mentioned above, factory can obtained power saving up to 23% of total consumption

Results of the project	
Total investment costs	IDR 65 million including new ultrasonic flowmeter for periodically checking
Energy saving	237 MWh/ year
Cost saving	IDR 327 million
Payback time	2.4 years
GHG emission reduction:	199 tons CO_2/year

6.4 Case 4) Installing new unit of centrifugal compressor in place of 4 existing units of oil-flooded screw type air compressors

Industry: Flour mill enterprise

Project summary: Flour mill industrial factory in Jakarta has implemented a project of installing a new centrifugal air compressor instead of 4 existing units of oil-flooded screwed type air compressor. The goal of the project is to reduce energy costs and greenhouse gas emissions.

Year of implementation: 2023

Status before implementation:
The plant is operating 4 existing units of oil-flooded air compressors with total capacity of 790 kW at total flowrate up to 117.2 m³/min. These are high-capacity air compressors, but their specific energy consumption (SEC) in generating compressed air is as high as 6.7 kW/(m³/min) and they consume a significant amount of oil during operation.

Figure 23 : Current oil flooded compressor

Result:
The plant has replaced them with the new high-efficient centrifugal compressor, which has better SEC as low as 4.8 kW/(m³/min). The new centrifugal compressor has a capacity of 577 kW and a flow rate of 120 m³/min, avoid the unloading mode during the operation because of relatively constant running at higher efficiency.

Figure 24 : New centrifugal compressor

Corresponding to the annual power consumption of new air compressor motor maintaining 8 kg/cm² pressure as follows:

Table 15: Performance Comparison Table of Two Condition of Air Compressor

Name	Capacity (kW)	Total Consumption (MWh/year)
Current Air Compressors	790	6,320
New Centrifugal Air Compressor	577	4,616

The new compressor saves about 1,704 MWh/year or 27% of power consumption compared to old air compressor.

Results of the project	
Total investment costs	IDR 6,000 million
Energy saving	1,704 MWh/year
Cost saving	IDR 1,874 million/ Year
Payback time	3.2 years
GHG emission reduction	1,431 tons CO_2/year

6.5 Case 5) Reduction of the inlet temperature to the compressor

Industry: Consumer goods industry

Project summary: A consumer goods industry in Jakarta Province has adopted a solution of inlet temperature reduction to air compressor.

Year of implementation: 2023

Status before implementation:
The compressor house is situated in a hot environment up to 45°C.

Figure 25 : Air intake temperature of compressor

When the air intake temperature increases by 10°C, the power consumption of the air compressor will increase by approximately 3.5%.

Result:
Hot air exhaust ducts have been installed for the existing 2 units of compressor at 37 kW. The temperature of compressor house was reduced to ambient temperature that directly improved compressor performance.
By lowering the temperature, the actual electricity consumption in the compressed air system is reduced by approximately 1.5% or 118 MWh/year

Figure 26 : Installed hot air exhaust for compressor

The actual power consumption of the compressed air system reduces by about 1.2%.

Results of the project	
Total investment costs	IDR 120 million
Energy saving	63 MWh/ year
Cost saving	IDR 69 million
Payback time	1.7 years.
GHG emission reduction	52 tons CO_2/year

6.6 Case 6) Exhaust hot air heat recovery system

Industry: Food and beverage industry

Project summary: A food and beverages enterprise in West Java-Province has adopted a solution of exhaust hot air recovery system from air cooled compressor for preheating of make-up boiler water. The goal of the project is to reduce energy costs and greenhouse gas emissions.

Year of implementation: 2019

Status before implementation:
The existing 2 units of air-cooled oil free-screwed type compressor with a power capacity of 75 kW at operating pressure of 7.5 bar, released exhaust hot air after cooling fan about 60-71°C based on thermal image measurement. This surplus heat was not recovered yet and was discharged to the atmosphere.

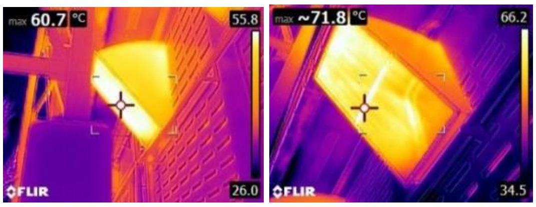

Figure 27 : Exhaust hot air after cooling fan discharged to the atmosphere

Result:
This surplus heat was recovered successfully using finned tube heat exchanger before discharging to the atmospheric. By pre-heating 3 m^3/h make-up water from 30°C to 40°C with surplus heat, the total annual energy saving was 308 MWh in gas fuel consumption of the boiler.

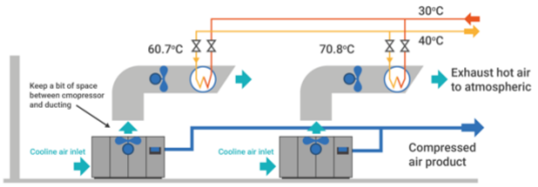

Figure 28 : Installed hot air exhaust for compressor

Figure 29 : Installed finned tube heat exchanger on the top of compressor after cooling fan

Results of the project	
Total investment costs	IDR 500 million
Energy saving	308 MWh/year
Cost saving	IDR 168 10 Million
Payback time	3 years.
GHG emission reduction	62 tons CO_2/year

6.7 Case 7) Heat recovery on high-pressure 35 bar piston compressor for boiler feed-water

Industry: Beverage industry

Project summary: A beverage enterprise in West Java-Province has adopted a heat recovery system by installing it at the compressed air after-cooler for preheating of boiler make-up water. The goal of the project is to reduce energy costs and greenhouse gas emissions.

Year of implementation: 2019

Status before implementation:
The existing 1 unit of water-cooled piston type air compressor with a power capacity of 450 kW at operating high pressure of 34 bar for blow-molding of plastic PET bottle, released compressed air after 3-stage at temperature about 123˚C based on thermal imager measurement. This surplus heat was not recovered yet and was discharged through the after-cooler to the cooling water return to cooling tower.

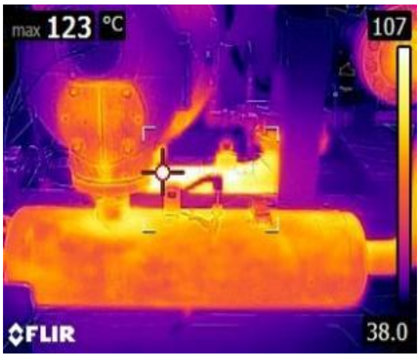

Figure 30 : Hot compressed air at point of 3 stage compressor

Result:
This surplus heat was recovered successfully using shell and tube heat exchanger before discharging to after cooler.
By pre-heating 3 m^3/h make-up water from 30°C to 60°C with the surplus heat, the total annual energy saving was 911 MWh in gas fuel consumption of the boiler.

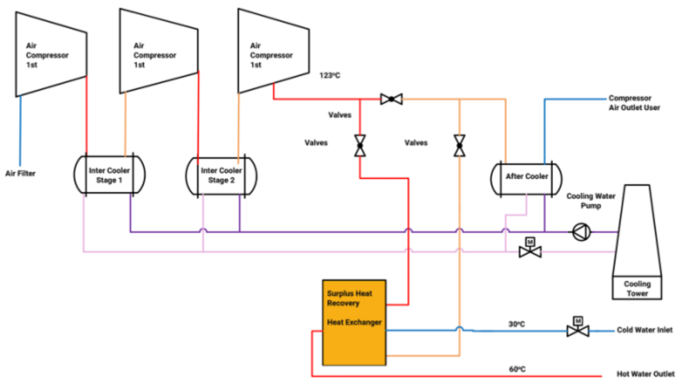

Figure 31 : Installed surplus heat recovery system using shell and tube heat exchanger

Results of the project	
Total investment costs	IDR 1,200 million
Energy saving	911 MWh/year
Cost saving	IDR 504 million
Payback time	2.4 years.
GHG emission reduction	184 tons CO_2/year

6.8 Case 8) Heat recovery on oil-flooded compressor

Industry: Footwear industry

Project summary: A footwear industry in West Java-Province has adopted a solution of hot oil flooded recovery system from screw-type compressor for low temperature hot-water generation for washing- and cleaning applications. The goal of the project is to reduce energy costs and greenhouse gas emissions.

Year of implementation: 2025

Status before implementation:
The existing 4 units of oil flooded screwed type compressor with a power capacity of 37 and 75 kW. Oil circulation inside-temperature was measured between 80-90˚C at an operating pressure of 6 bar. This surplus heat was not recovered yet and was cooled by cooling fan. Meanwhile, this industry has been generating hot water using electric water heater.

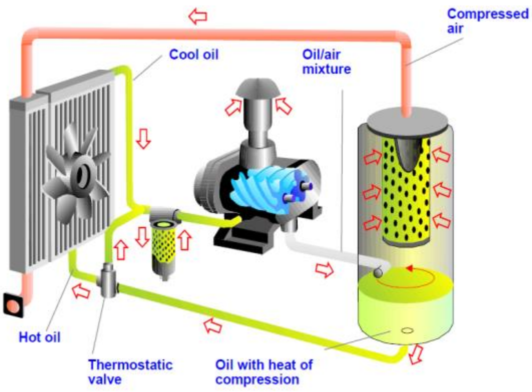

Figure 32 : Working principal of oil flooded-screw type compressor

Result:
This waste heat was recovered successfully by using a plate heat exchanger before the cooling fan. By pre-heating 5 m^3/h make-up water to 40°C with the surplus heat, the total annual energy saving was 403 MWh in electricity consumption of the boiler.

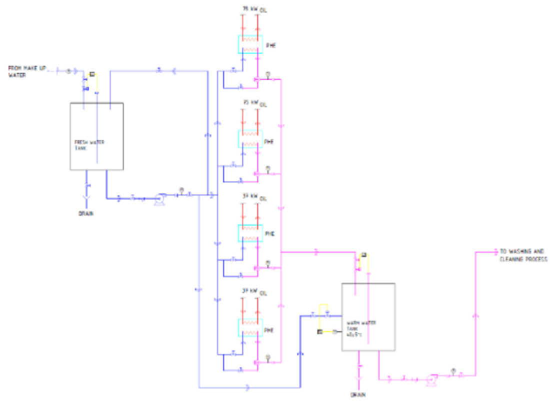

Figure 33 : Heat recovery system for oil flooded compressor

Results of the project	
Total investment costs	IDR 1,200 million
Energy saving	403 MWh/year
Cost saving	IDR 443 million
Payback time	2.7 years.
GHG emission reduction	339 tons CO_2/year

6.9 Case 9) Replace choked air filter using new one with higher capacity

Industry: Food industry

Project summary: A food industry in West Java-Province has replaced choked air filter using new one with higher capacity. The goal of the project is to reduce pressure drop that leads to energy costs and greenhouse gas emissions.

Year of implementation: 2025

Status before implementation:
Filters use energy in terms of the introduced pressure drop in the system. To obtain a pressure profile between before and after air filter, a pressure data logger was installed during compressed air audit. Existing pressure drop was found to be 15.6 psi (1.07 bar) and too high due to choked filter.
For every 0.2 bar the pressure drops across choked filters, the compressor power consumption increases by about 2%.

Result:
Furthermore, the filters should be checked regularly to ensure minimum pressure drop during operation or replace with the new one. After replacement with the new filter with higher capacity, the pressure drop was reduced to be 7.99 psi (0.54 bar). Thus, total reduced pressure drop was calculated at 7.61 psi (0.52 bar). The compressor power consumption was also reduced by 5.2% or 122 MWh annually.

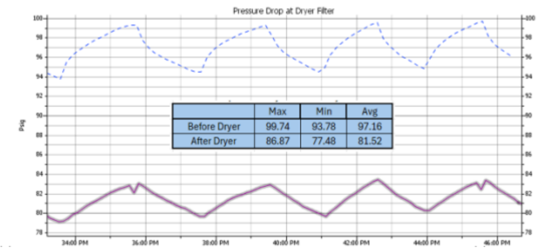

Figure 34 : Pressure drop before and after dryer

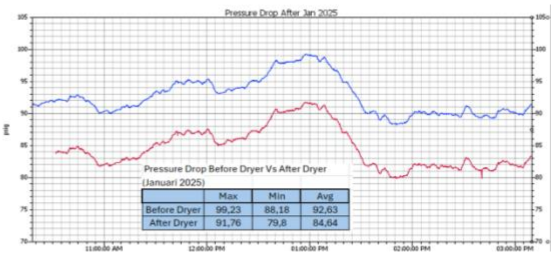

Figure 35 : Heat recovery system for oil flooded compressor

Results of the project	
Total investment costs	IDR 90 million
Energy saving	122 MWh/year
Cost saving	IDR 146 million
Payback time	0.6 years.
GHG emission reduction	tons CO_2/year

6.10 Case 10) Pressure reduction (example from Vietnam)

Industry: Footwear Industry

Project summary: A footwear company in Thanh Hoa Province has installed a loop circuit system and reset the operating pressure of the compressor. The goal of the project is to reduce energy costs and greenhouse gas emissions.

Year of implementation: 2024

Status before implementation:
The installed pressure (6.5 - 8.1 bar) was higher than the demand in the factories:

- Sewing machine: 3.5 - 4.5 bar
- Base cleaning machine: 1.0 bar
- Automatic cutting machine: 4.0 - 5.0 bar

Compressed air pressure at the end of the workshop (6.6 - 7.3 bar) was higher than the required level.

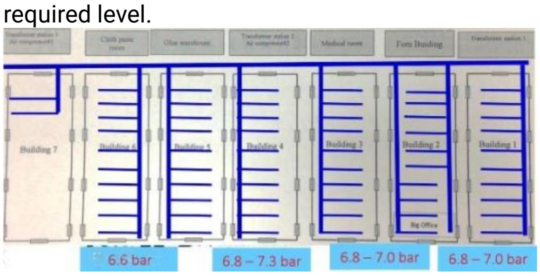

Figure 36 : Diagram of existing compressed air distribution at the factory

The factory's existing compressed air distribution system is fishbone-shaped circuit system.

Result:
The factory has installed a closed loop pipeline for the distribution and regular pressure valves of compressed air on the 2nd floor of the building 12.

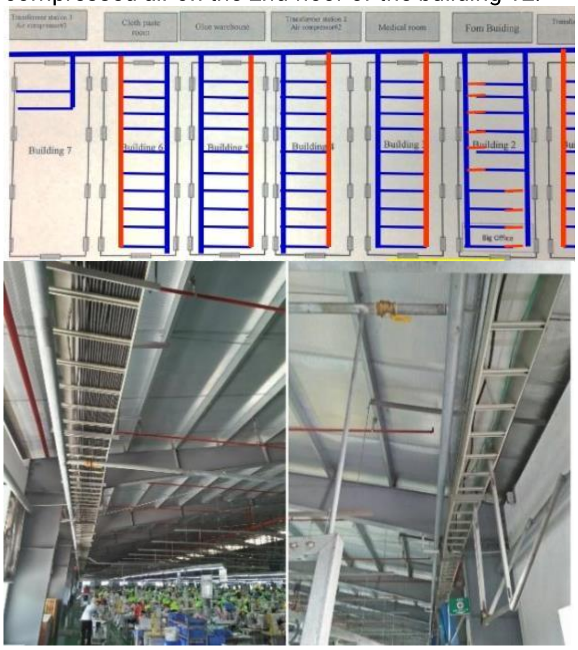

Figure 37 : Compressed air loop circuit diagram and image after adopting the solution

The pressure loss at the door and end of the workshop is about 0.2 bar compared to 1.0 bar before Therefore, the factory can reduce the installed pressure of the compressed air system by about 0.8 bar.

Results of the project	
Total investment costs	IDR 32 million
Energy saving	65 MWh/year
Cost saving	IDR 76 million/year
Payback time	0.42 year
GHG emission reduction	55 tons CO_2/year

6.11 Case 11) Best practice (example from Denmark)

Industry: Dairy

Project summary: A dairy in Denmark had various compressed air compressors ranging from 10 to 20 years old. After measuring the overall efficiency, it was decided to replace the entire installation and implement heat recovery from the cooling system.

Year of implementation: 2024

Status before implementation:
The dairy operates 8,400 hours per year and had six different air compressors of various sizes, all supplying a common system.
The annual compressed air consumption is 10.2 million m³.
Prior to the project, measurements of electricity consumption and compressed air production were carried out over the course of a week. The measurements showed an average specific electricity consumption of 0.132 kWh/m³.

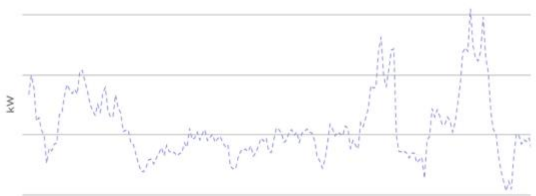

Figure 38 : The load varies throughout the week. The measurement accounts for both operating and idle periods, as well as the complete installation including the air dryer

Investment decision:
A project of this nature could, under the subsidy scheme described in section 1.2.3, receive a grant of 6 million IDR, which helped to reduce the investment cost and made the project possible.
The dairy also values the CO_2 savings, and when this is taken into account, the simple payback time is reduced to five years.
However, the project was not decided based on the simple payback period, but rather on the Total Cost of Ownership over a ten-year period, where energy savings carry significant weight.

Result:
The project replaced the existing supply system with six air compressors with a new system consisting of two compressed air compressors with associated adsorption dryer. The two new compressors are sized to handle the entire demand.

Figure 39 : The new installation with the adsorption dryer in front and the air compressor behind

Measurement of consumption and production over a week was repeated after the installation. The annual electricity consumption dropped from 1,346 MWh to 984 MWh.
The two new compressors have built-in heat exchangers for water cooling, and the recovered waste heat replaces natural gas consumption in the boiler system.
Replacing six older compressors with two new ones also reduced maintenance costs.

Results of the project	Note that prices and emission factors are Danish
Total investment costs	IDR 79 million
Energy saving, electricity	362 MWh/year
Energy saving, natural gas	324 MWh/year
Cost saving, electricity	IDR 8 million/year
Cost saving, heat recovery	IDR 2 million/year
Cost saving, maintenance	IDR 2 million/year
Payback time	6.1 year
GHG emission reduction	92 tons CO_2/year


25
50
75
100
125
150
200
0
2
4
6
8
10
12
14

7 The procurement process for new compressed air systems

Procuring new air compressors and a complete compressed air system represents a significant investment for most industries and requires careful planning to ensure a sustainable and cost-effective solution. The procurement process should be scaled appropriately to the size and complexity of the project, as the requirements can differ substantially depending on whether the objective is simply replacing an existing air compressor or installing an entirely new system. This section focuses on the procurement process for large-scale investment projects.

For the large investment the procurement process should follow the steps below:
1. A pre-feasibility phase
2. A feasibility phase
3. A tendering phase
4. A tender evaluation phase

Following the tender evaluation phase, the next steps typically involve implementation, testing, and commissioning of the compressed air system. However, these phases are beyond the scope of this section and will not be covered here.

7.1 Pre-feasibility phase

The aim of the pre-feasibility phase is to define the project to carry out and evaluate alternative overall solutions so as it can be concluded what the most attractive way forward will be.

During this phase, many industries face the dilemma of choosing between a low-cost, less efficient solution and a more expensive, energy-efficient option with lower long-term operating costs. It is strongly recommended that these alternatives be thoroughly evaluated and well-documented to enable management to make an informed and strategic decision.

Another important consideration before initiating the procurement process is whether the current production setup will remain suitable for future needs.

The simplest approach is often to proceed with installing new equipment without further analysis. However, a more thorough investigation may reveal alternative solution strategies that offer greater long-term value. Therefore, a pre-feasibility phase should be conducted to carefully assess and document the project's design basis, while systematically comparing key elements of the proposed solution strategies, for example, system layout, capacity requirements, and energy efficiency.

1. What is the purpose of the project?

It is important to be precise about for which reasons a new compressed air system installation is to be considered.

The most common reasons for initiating a new project regarding compressed air will be the need for more capacity or because severe outages in the compressed air system are experienced.

However, a new compressed air system can also offer a range of other benefits, such as:
- Reduced operational costs (including energy, staff and maintenance)
- Pressure and airflow to match better with demand
- Improved working environment
- Reduced carbon footprint
- Compliance with the current regulation
- Increased market value of the product as a result of lower environmental impacts.

The combined value of these benefits could very well supersede the value of the energy cost savings. It is important, therefore, to consider these already in the pre-feasibility study and highlight those that are deemed most important.
However, a strategy to become more energy- and cost efficient or to reduce carbon emissions can be the reason for starting a project.

2. What is the scope of the project?
A new project can cover the replacement of a worn-out compressor, but it can also be a project covering the implementation of a whole new system covering compressors, piping etc. A compressed air-project can therefore be quite comprehensive and will include different disciplines and engineering works to plan and include in the investment estimates.

However, for all cases the expected scope of the project shall be described to make it clear for all relevant parties which works that are underway.

3. Which demand is to be covered?
An important component of the pre-feasibility study is conducting a comprehensive assessment of pressure levels and compressed air demand. This also includes taking any further expansions into consideration.
Besides knowing the demand, this mapping shall also help with identifying any energy saving possibilities as discussed in section 1, like reducing the pressure level and air flow demand.

4. Which technology to use?
There are multiple ways of building up the compressed air system. Which compressor type to use, how should the distribution system be configured?

Use the purpose from point 1 to choose from the possibilities described in section 5. When choosing, bear in mind that the energy and maintenance cost will be a large part of the expense over a period of time, see Figure 39 . It can therefore make sense to invest in the more efficient technology, even though it is more expensive, to reduce the energy and operation cost over the lifetime and improve the Total Cost of Ownership (TCO) of the investment.

TCO, Total Cost of Ownership, is the recommended method for evaluating different possible solutions. A span of year is selected e.g. 10 years as the lifetime of a CAS is more than 10 years.

The following four parameters must be included in the calculation of the TCO:

- Investment; use the net investment after possible grant have been deducted
- Operation & maintenance; total costs for operation and maintenance every year in the selected time span
- Energy costs; total costs for energy every year in the selected time span
- Disposal costs: one time cost at the end of lifetime, but if the lifetime is longer than the selected time span this cost can be excluded

By incorporating these parameters into a discounted cash flow analysis, supported by thorough evaluations, the best possible foundation for making an informed investment decision can be established. In many cases, the initial investment cost accounts for only 10% to 20% of the total costs over a 10-year period. This underscores the importance of selecting energy-efficient equipment from the outset.

When the technology and system build-up have been chosen a fairly accurate investment budget (CAPEX and OPEX) should be made, so that the management can allocate funds for the project. Furthermore, documentation of the current energy performance should be gathered to be able to compare the energy performance after the installation and conclude whether the energy saving is realized.

As a conclusion of pre-feasibility, a report must be made describing the purpose of the project, the design basis for the project and expected investments (CAPEX) and expected operation costs (OPEX) should be assessed for each alternative solution identified.

As such, the pre-feasibility report shall describe the business case for the project including relevant alternative solutions. The business case shall include an assessment of Total Cost of Ownership (TCO) for alternative solutions calculated as Net Present Value (NPV).

The report shall be presented for the management in the company to decide on further steps, and often it should also be recommended also to initiate a dialogue with the bank regarding financing options for alternative solutions. Some banks will have attractive loan and financing options for sustainable solutions, which should be identified already in the early stages of the project development as this can have significant impact on financing costs etc.

Based on meetings with the management, the next steps should be decided. The scope of the project shall be described in a concluding memo and the feasibility phase initiated.

7.2 Feasibility phase

The aim of the feasibility phase is to carry out a preliminary solution design for the preferred solution and make a fairly accurate investment budget (CAPEX and OPEX) so as the management of the company can allocate funds for implementing the project.

Input and knowledge of suppliers are important and beneficial when carrying out the feasibility study and can also give new inspiration to the configuration of the compressed air system and the preferred solutions. Further, vendors can assist with more accurate budget prices.

The feasibility study and the following feasibility report must include all elements necessary to achieve the most optimal solution and may include topics such as:

- Project scope
- Detailed description of the project
- Optimizing the demand to cover
- Optimization of Total Cost of Ownership (TCO) over a ten-year period
- Financial analysis, i.e. investment and operation costs (CAPEX and OPEX)
- Financing options (e.g. subsidies)
- Assessment of impacts on the operations of the enterprise
- Assessment of other impacts
- Project risks
- Overview of approvals and legislative framework
- Time schedule for implementation
- Project organization incl. preferred suppliers
- Recommendations for next steps

The outcome of the feasibility study is a report to be used as basis for the management's decision on investment. Finally, the feasibility study shall be presented to the management to get approval of funds for the investments (CAPEX).

7.3 Tendering phase

Based on the feasibility study and approval of CAPEX from the management, the detailed project preparation will comprise a number of phases.

7.3.1 *Final scope definition*

The exact scope of the contract must be established, and the following items will usually be included:

- Complete compressed air-installation
- Electrical connection
- Control strategy and system (Interface to current control system)
- Delivery and assembly
- Insulation
- Commissioning (in close cooperation with the owner)
- Trial operation
- Noise measurement
- Documentation incl. energy performance and savings
- Hand-over and final project conclusion
- Spare parts and service contract (option)

The list above is highly depended on the actual project being performed.

7.3.2 *Technical specifications*
The requirements to equipment must be described unambiguously. It is particularly important to describe the overall delivery performance:

Environmental:

- Noise requirements

Functionality

- Airflow and pressure provided.
- Total efficiency of the system
- Max electrical consumption (at 100% load).
- Piping and connections should be free for leakages (If new piping are installed)
- Control strategy.

Definition of how the performance test shall be conducted. It is important to be very specific to avoid discussion on methods, timing, sampling, calculation afterwards.

It shall also be described how deviations shall be handled and what shall be fulfilled before a handover can take place.

7.3.3 *Performance guarantees*
Before setting the conditions for the performance guarantees it is important to evaluate the operation conditions to make sure that it is possible to make the test runs.

7.3.4 *Service contract.*
Taking spare parts and service of the compressed air system into the contract will result in a fair price for the operation in the coming years.

7.4 Contracting phase

The quotation evaluation has two main purposes:

- Identifying deviations from the tender documents
- Making the tenders comparable enabling price negotiations

In the technical clarification, it is important to take a deep dive in the two most attractive quotations to ensure that there are not misunderstanding and deviations from the tender documents which are not immediately apparent.

After this clarification and final price negotiation, a contract can be completed.

7.5 Later project phases

It is important to follow the installation and commissioning phase closely to monitor whether important design decisions in the feasibility and tendering phase are followed through.

After the project have been installed and been operating it is important to conduct a general evaluation. To do so it is important to collect and document the new energy performance. This is both in relation to the performance guarantees but also whether the energy saving have been achieved as it may have been one of the main reasons for the project to initiated in the first place. The evaluation of the project could for example cover:

- Did it deliver the calculated energy reduction?
- Was it finished within the budget?
- Does the new system function as wanted?
- Does there exist further optimization potential, which can be investigated later?

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Appendix

APPENDEX 1: CHECKLIST FOR ENERGY OPTIMIZATION OF COMPRESSED AIR SYSTEMS

Check the following:	What to do:	Potential:
Compressed air demand		
Alternatives to compressed air	Check for alternatives to compressed air, see .	
Pressure level	If the system pressure is more than 1,3 bar above the required pressure from the user, take actions into reducing it, see section 4.2	For every 1 bar the pressure can be reduced the electricity consumption decreases with 8%
Air flow demand	Check the need at the end user whether it can be reduced, or alternative sources can be used.	Only 10-15% of the input energy is utilized at the end user.
Plant efficiency		
Compressor efficiency	Check that the compressors efficiency corresponds to the benchmarks listed in Figure 15: .	
Room temperature	The inlet air to the compressor should be below 35°C.	For every 10°C decrease in the inlet temperature the energy consumption is reduced with 3,5%
Pressure loss in piping	Pressure loss should be reduced as much as possible. Use as large a diameter for the main pipe as possible. Pressure loss in piping should not exceed 0.2 bar from compressor and to end user.	For every 1 bar the pressure can be reduced the electricity consumption decreases with 8%
Buffer storage	If no buffer storage is present installing buffer storage can help with better control, reducing pressure level etc. The buffer capacity in m^3 should be 6-10 times bigger than air flow in m^3/s.	
Heat recovery	Make sure to recover the heat from the compressor if it can be utilized elsewhere e.g. for space heating.	Up to 80% of the input energy can be recovered as heat in a water-based system.
Drying	Do not dry more than necessary. Use a cooling dryer where possible and if a desiccant dryer is needed use the one utilizing	

	excess heat from the compressor for regeneration.	
Control strategy		
Time control	Shut off compressors when there is no production.	
Use shut off valves	If the plant is using sectioning the section not in production should be automatically shut off by using valves.	
Cascade control	With the use of multiple compressors, it is important to always run the combination with the highest efficiency.	
VSD-controlled compressor	With multiple compressors one should always be controlled by a VSD and be the first and last to stop.	
Maintenance		
Air leaks	Regularly check for air leaks with proper tools. See section 4.6	Air leaks can account for 30% of the produced compressed air.
Filters	Regularly check filters and replace dirty ones.	To overcome dirty filters the compressor increases the pressure, and for every 1 bar the pressure is increased the electricity consumption increase with 8%
Reduction valves etc.	Regularly check and tighten valves in the piping system to prevent air leaks.	
Transmitters	Regularly calibrate and check pressure transmitters and pressure switches.	
Monitor KPI's	Setting up KPI's for your plant can help maintain the efficiency of the plant and help identify possible improvements. The recommended KPI's are listed in .	

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