System Efficiency Policy: The Next Level of Energy Savings

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ABSTRACT

Minimum efficiency performance standards (MEPS) and energy labels are amongst the most widely used policy instruments to increase energy efficiency, particularly for energy-using products in the residential and commercial sectors. These policy instruments are effective and cost-efficient. However, policies with a broader scope, such as a focus on systems, could address a larger share of the energy consumption in an integral way and increase energy savings. Policy makers need to consider diverse strategic issues when pushing for this next frontier in energy efficiency policy because of a range of regulatory issues.

This paper first estimates the energy savings potential worldwide, enabled by a system efficiency policy approach to be 4,780 TWh/year, equivalent to 9 % of global energy use.

Secondly, the barriers in the regulatory process associated with introducing system efficiency policy are discussed, and the paper provides suggestions for overcoming these challenges. It discusses the importance of suitable verification procedures and robust test methods for system policy. Further the paper includes an analysis of the changes in a systems approach regarding the responsibility of actors in enforcing a regulation. The difficulties in regulating systems and the solutions achieved to date are illustrated for the cases of walk-in cold coolers and freezers (in USA) and water pumps (in the EU). The paper concludes by mapping regulatory solutions for various types of systems.

Introduction

Why would policy makers look at energy-using systems? The simple answer to this question is that systems offer large possibilities for energy savings. Savings from more efficient electric motors are estimated in the range of 3 to 5 %, while cost-effective savings for the motor system, i.e. the electric motor, the variable speed drive (VSD) and pump or fan together can easily be 20 to 30 % (IEA, 2016). In many countries the energy efficiency of many products is already regulated through minimum efficiency performance standards (MEPS) and labelling, while systems are not; see IEA 4E (2021) for an overview of energy efficiency standards and labelling programmes. As policy makers show a strong interest in exploring how systems could be regulated to increase energy efficiency, it is not obvious how to extend or transform efficiency policy to energy-using systems.

This paper approaches this challenge by starting with a definition of a system and a classification of systems. We provide estimates of the worldwide energy savings potential for various systems, and then identify the regulatory challenges. We suggest approaches and map these approaches to regulate systems to the main elements of the classification. Also we describe two examples of regulatory approaches, for walk-in coolers and freezers (in USA) and water pump units (in the EU). The paper closes with conclusions and recommendations, including a mapping of regulatory solutions for a number of systems.

Definition and classification of systems

We propose the following technical definition of a system:

a system is a functional unit that consists of two or more physical parts that need to be assembled at the location where the system is used.

In order to function on site, energy-using systems need to be assembled *and* installed. Assembly means putting the parts together to form the system. Installation means connecting a system (or a product) to another system in a given environment, e.g. an electricity or gas grid or a water or air piping system.

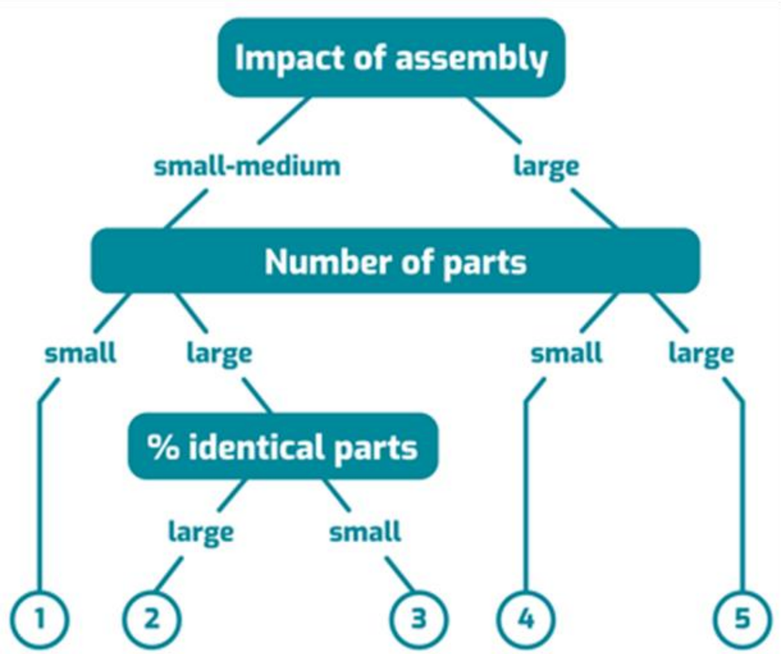

Figure 1. Classification tree for the different classes of systems (Siderius et al., 2021).

This definition brings two aspects to explore regarding the challenges of regulating systems: the concepts of “parts” and “assembly”. In Siderius et al. (2021) we developed a classification of systems based on the impact of assembly on energy consumption or performance, the number of parts and the percentage of identical parts. Figure 1 shows the classification tree, where in general the system complexity increases from left to right. Examples of systems according to the classes shown in Figure 1 are:

① An electric motor with variable speed drive (VSD) plus fan or water pump or a multi-split air conditioning system with one outdoor unit and several indoor units.

② A lighting control system (with standardized parts) for an office building.

③ A building automation control system (BACS) for a home with standardized parts (impact of assembly is small) providing a large number of functions (heating, lighting, security, etc.); where the number of parts is large but the percentage of identical parts is probably small.

④ A walk-in cooler-freezer.

⑤ A compressed air system for a factory, including the piping.

Energy savings potential for systems

To estimate the energy savings potential for systems we identified systems with large energy consumption that are suitable for extending product policy to systems. We quantified their energy consumption and the technical savings options for these systems, and estimated the applicability of the technical savings, i.e. the proportion of the market to which the technical savings could be applied.

The industrial sector systems with high energy consumption were identified from published industrial energy data in the IEA World Balance Sankey diagram combined with the US DoE dynamic manufacturing energy Sankey tool: building heating and cooling, steam systems, and motor systems i.e. compressed air, pump and fan systems. In the commercial and public sectors, street lighting and cold rooms were also identified as candidate systems based on such estimates where information was available.

A number of systems were not included for various reasons. For example, systems which are better addressed for efficiency through their specific industries, e.g. those used in aluminium smelting or agriculture. For other systems there is limited information, such as materials handling (e.g. belt conveyors) and materials processing, which already may be an indication of difficulties in addressing their energy efficiency. Finally, multimedia and information and communication technology systems appear to be likely candidates, but again there is limited information or data to assess their energy savings potential in our study. Given this partial coverage of the energy-using systems, the energy savings estimates identified in this paper are likely to be underestimated.

Most energy savings reported were identified and quantified in the context of retrofitting existing systems to increase their energy efficiency. The maximum technically achievable savings can range from 10 to 60%, but are highly dependent on the details of each individual system. The savings considered as relevant for product policy were those resulting from efficiency gains of the components, from the overall system design and from improved controls to match changing demand. Also energy savings by better maintenance were included, under the assumption that better design, assembly and control systems set by policy requirements could reduce system failures, enable and even encourage better maintenance. These technical savings are shown in Table 1. The percentages relate to the global energy consumption of the system. It was found that system, control and maintenance savings were frequently two to three times higher than component savings alone, which provides already evidence that the systems approach has greater potential for saving energy.

Table 1. Reported technical savings for selected systems

System	**Component**	**System design**	**Controls**	**Maintenance**	References
Compressed air	9%	14%	5%	14%	McKane and Hasanbeigi (2010)
	5%	20%	10%	10%	Radgen and Blaustein (2001) in Saidur et al. (2010)
	13%	17%	9%	16%	Xenergy Inc. (2002)
Pump systems	11%	19%	0%	14%	McKane and Hasanbeigi (2010)
	5%	60%	0%	2%	Xenergy Inc. (2002)

Fan systems	2%	19%	0%	8%	McKane and Hasanbeigi (2010)
	5%	30%	0%	2%	Xenergy Inc. (2002)
Steam system	15%	22%	0%	2%	Hasanbeigi (2014) (low base case)
	7%	11%	0%	1%	Hasanbeigi (2014) (high base case)
	19%	17%	0%	19%	Einstein et al. (2001)
Street lighting	0%	25%	0%	no data	Mjøs (2007), Ożadowicz and Grela (2017), Petritoli et al. (2019), Donatello et al. (2019)
Commercial buildings	6%	10%	27%	no data	Regnier et al. (2018), Jeon (2016), Kim et al. (2019), Ligade and Razban (2019), Lu and Warsinger (2020)

Since not all the technical savings are applicable to the entire market, either because they do not apply to the given system or they have already been adopted, the policy applicability was adjusted to give a more adequate estimate of the policy savings, expressed as a percentage of technical savings. The policy savings are around 20 to 30% as shown in Table 2, with markedly higher potential energy savings for commercial building heating due to their still large energy consumption.

Table 2. Energy savings estimates for selected systems, worldwide

System	**Technical savings (Energy consumption)**		**Policy savings**	**Total savings**	
	PJ	*TWh*		*PJ*	*TWh*
Compressed air	2,540	700	30%	760	210
Pump systems	3,880	1,080	24%	930	260
Fan systems	2,580	720	10%	260	70
Steam systems	43,000	11,940	24%	10,320	2,870
Cold rooms	180	50	20%	40	10
Street lighting	510	140	23%	120	30
Commercial cooling	4,930	1,370	24%	1,170	330
Commercial heating	12,860	3,570	16%	2,020	560
Residential heating	31,810	8,830	5%	1,590	440
All systems	102,280	28,410	17%	17,210	4,780
All systems (excl. Steam systems)	59,280	16,470	12%	6,890	1,910

For the nine systems considered across the industrial, commercial and residential sectors, the combined consumption reaches over 100,000 PJ (28,000 TWh) of final energy annually, and represent 54% of (fossil) fuel and electrical energy consumption across these sectors worldwide. The potential energy savings are approximately 17,000 PJ (4,780 TWh), equivalent to 9% of global energy use. Over half of these energy savings are accounted from the steam systems alone, but excluding these, still savings of 6890 PJ (1910 TWh, 4% of global energy use) would be possible.

Regulatory aspects and challenges in regulating systems

In general energy efficiency measures need to cover the following main elements:

- The scope: which products or systems are included and/or excluded and who is responsible for complying with the regulation -i.e. the addressee(s).
- The (efficiency) metric(s) and the requirements.
- The verification and enforcement, including test methods.

The power to regulate is also an important aspect. Each of these elements are discussed next.

Scope and addressees

The scope is mostly defined in relation to the (main) function(s) and/or the characteristics of the system, and often results in a "technology neutral" scope, i.e. all systems that fulfil the indicated function(s) are in scope, regardless of the technology used. For functions such as moving air or pumping liquids, both products and systems can provide the same function. In this case, a regulatory level playing field is only achieved if both would be in the scope of the regulation and are subject to the same requirements. Defining the system boundaries is also important to set the scope of a regulation, as well as considering the conditions of use and their impact. Tying the scope too closely to certain given conditions of use could bring the risk of falling out of the scope and thereby of the regulated requirements. Therefore, the scope needs to be formulated in a general way, which in turn could result in the inclusion of a large number and variety of usage conditions.

The system definition implies that different possible addressees need to be considered - the manufacturer of the parts, the company that offers the system to a customer, the customer that specifies the system, or the company that assembles (and installs) the system. The impact of the assembly would also influence the choice of the addressee: if the impact is large, it would be logical to include also the assembler as an addressee. Finally, the number of addressees is relevant for verification and enforcement. In general, a small number of addressees makes monitoring verification and enforcement activities easier.

Efficiency metrics and requirements

Efficiency relates output (performance) to input (energy) – or vice versa. In principle, an efficiency *metric* can always be formulated since by definition every system has a function and uses energy. However, it is not always easy to quantitatively define and measure performance. The setting of requirements can be difficult because, as discussed before, the energy consumption and performance of the system depend on the design, the assembly and the location where the system is used. Therefore, the requirements need to account for these conditions, and the test methods need to reflect these conditions.

Another aspect is the relationship between setting requirements for parts of the system and the requirements for the whole system. Firstly, efficient requirements for single parts may not always lead to achieving a high efficiency for the system. An efficient electrical motor and an efficient VSD can work together in a way that is inefficient. Only an optimal mutual alignment turns the (two) parts into an efficient system, and this relationship needs to be considered with regards to setting requirements. Secondly, it might be that setting a requirement for the system makes requirements for the individual parts superfluous. If both, the requirements for the parts and the system requirements can be measured, the requirements for the parts could be considered unnecessary. However, verification may depend on testing parts of the system and deriving the result for the system via a model. To ensure the correctness of the input data for modelling, setting requirements for the parts could be useful. Moreover, parts used in regulated systems may also be used as standalone parts, or even be parts of other non-regulated systems. Since in practice it is impossible to differentiate between a part used in a regulated system and elsewhere, this could result in the parts used elsewhere not being regulated.

Verification and enforcement – including test methods

Verification needs to consider all aspects discussed above: the scope and addressees, the efficiency metric(s) and requirements. Only systems in scope of the regulation can be verified for compliance with the requirements according to the metrics, and the addressee is responsible for compliance. If addressees are difficult to identify, a regulation is difficult to enforce. A verification method that requires cooperation of an addressee may also be difficult to enforce, especially if the cooperation itself cannot be enforced.

Although verification can be done in different ways, test methods are usually an essential part of the verification process. The main purposes of a test method is to measure the characteristics of a system in an objective way, i.e. the results of the test should reflect the characteristics of the system, and not the conditions of the test or the test equipment. Test results need to be reproducible e.g. when tests are done at different testing laboratories. The testing standards specify in detail the test conditions, and define admissible deviations, accuracy and handling of the test equipment. However, a test method should also be representative, i.e. the test conditions, including the given operation of the system, should reflect the location where it is used and how it is used. Repeating the test at various conditions to reflect the (prevailing) locations where the system is to be used would quickly result in very high testing costs. Testing using a worst-case condition, or testing for fewer conditions and using interpolation of results for other conditions could help reduce testing efforts and costs.

The challenges for verification and testing regarding the location where the system is assembled and to be used, are the following Although the documentation of a system can be verified in the same way as for a product, a system can only be tested as such when it is assembled and installed at its intended location of use. The location of testing can in some cases be a laboratory. For the case of physically large systems, a test in the laboratory might not be robust enough to reflect the system conditions at its point of use, as the quality of assembly may be different. Moreover, for testing at the location where the system will actually be used, the market surveillance authorities need to have access to that location, but at that location it may not be possible to meet the conditions specified in the testing standard. Furthermore, it is difficult to test a system that is already in operation, since this would disrupt essential processes e.g., in a factory or commercial site; so, systems on location would need to be tested before starting operation. This then requires the surveillance authorities to know when a system is assembled. If the system requirements are not met, remediation is likely to be more complex and expensive than for a single product.

Three levels of verification (including any combination of them) could be used in a systems regulation, as follows:

- System level: the system is tested as assembled, and modelling with a scale model covers for the full "operational" range of the system.
- Part level: all parts of the system are tested and results for the system are derived from a mathematical model.
- Assembly process: the quality of the assembly is checked.

Regulatory powers

Beyond the content of energy efficiency measures to regulate discussed above, another important aspect is the status of the regulatory powers of the relevant authorities (e.g. ministries, surveillance authorities) to adopt, execute and enforce measures. This can relate to the scope, the territorial jurisdiction or the powers of surveillance authorities. Systems may not be in the scope of existing regulatory powers. Federal or National authorities may not have jurisdiction over systems that are assembled in a state or province. Surveillance authorities may not have the power to enforce cooperation in case of testing or assessing a system on location.

While regulatory powers can be changed, this generally involves changing higher order legislation, often in a slow and difficult process.

Approaches to regulating systems

This section presents an overview of methodological approaches to assess systems, since assessing the efficiency and performance of systems is at the heart of regulating energy efficiency. This also relates to the three verification levels presented before. Then we map the approaches to assess systems based on the main elements of the classification, and give examples of approaches from the USA and the EU for regulating selected systems.

Methodological approaches for assessing systems

The following methodological approaches for assessing systems exist, see Table 3, noting that in practice a blend of these may be used.

Table 3. Methodological approaches for assessing systems

Approach	Description
Black box approach	The black box approach does not care what is inside the system (the box); the relevant inputs and outputs of the system are assessed. This is the product testing approach (in a laboratory) applied to a system.
Modular approach	The modular approach focuses on assessing the parts (modules) of the system. Performance and energy consumption data of parts are measured/assessed and then combined in a formula to obtain the performance and energy consumption or efficiency of the system. This approach can resemble the modelling approach (see below), especially when a complex formula is used. The difference is that in the modelling approach usage conditions and/or operational range are included *in the model*, whereas in the modular approach these aspects are assumed to be taken into account in the assessment of the modules (parts), and a formula is then applied to combine the results.

Procedural approach	The procedural approach focuses on the assembly and installation of the system. This could include rules for sizing the system and its parts. In principle no testing (measurements) on parts are needed (but information on parts may be needed). This approach resembles quality management. The assumption is that if the right procedure is followed then the efficient functioning of the system is guaranteed. The steps of specifying parts, assembly and installation are documented and can be checked/verified.
Statistical approach	The statistical approach relies on measurements of energy consumption and performance when the system is in use. Energy use or power consumption, performance, usage and operational conditions are assessed. The values for the relevant efficiency metric are then statistically extracted from this data, allowing e.g. to correct for variations over time. This approach is used in monitoring installations, but could also be used for verification/certification, showing that a system performs as specified.
Modelling approach	The modelling approach comes in two main variantions. The first uses a mathematical model of (parts of) the system to calculate the performance, energy consumption or efficiency based on design parameters of the parts. The second uses a scale model of the (parts of the) system on which measurements are done. The results are scaled up to achieve results for the system. In each case the performance of parts could be checked independently.

A first indication of the applicability of the various approaches follows from mapping them to the main elements of the system classification and the variation in usage or operational conditions; see Table 4 below where the X marks the situation that is most suitable.

Table 4. Mapping approaches for assessing systems according to the systems classification and the conditions of usage

	Impact of assembly		**Number of parts**		**% Identical parts**		**Variation in conditions**	
Approach	*small*	*large*	*small*	*large*	*large*	*small*	*small*	*large*
Black box	X		*		*		X	
Modular	X		X		X		X	
Procedural		X	*		*		*	
Statistical		X[#]	*		*			X[#]
Modelling	X			X		X		X

* Element not relevant for the approach; [#] Approach can only be applied once the system is in use.

From this brief analysis we notice first, that in case the impact of assembly is large, the procedural approach should be included. Furthermore, modular and modelling approaches can cover the different situations regarding number of parts, percentage of identical parts and variations in conditions (usage, operational). The black box approach can cover situations that are similar to testing a product.

If the percentage of identical parts in a system is large, then it would be helpful to (only) regulate the parts. If the number of parts is large, but the percentage of identical parts is low or medium, the system consists of a medium to large number of different parts. Then it is possible to have a large number of system variants. In that case the regulation would need to include modelling. Another option is to check whether any of the parts are critical for the energy consumption, and regulate these parts.

Verification and test methods have to deal with both variety of the systems and variety of the usage conditions and operational range. If the variety is large, testing all variants may not be feasible regarding time and costs. In this case, modelling could be useful or even necessary. Table 5 considers the variations of usage and operational range within the modelling approach. If modelling is included in the measures, the regulation should include the calculation or simulation model. Alternatively, the regulation should indicate how third-party calculations or simulations should be verified for compliance with the regulation.

Table 5. Modelling approaches by type of measurement and variations

	Variation in usage conditions	**Variation in operational range**
Measurement of *system*	Uses the test results at system level, measured for a limited number of usage conditions, to calculate system results at other usage conditions.	Uses the test results at system level, e.g. from a scale model, to calculate results for larger systems.
Measurement of *parts*	Uses the test results for parts as input for a model that covers different usage conditions; the model simulates the system, i.e. the energy or performance relevant interaction between the parts.	Uses the test results for parts as input for a simulation model that covers the total operational range.

Examples of regulating systems

Walk-in coolers and freezers (WICF): in the USA the Energy Policy and Conservation Act (EPCA) established the Energy Conservation Program for Certain Industrial Equipment, including components of walk-in coolers and freezers (WICF). EPCA also directed the US Department of Energy (DOE) to establish test procedures to measure the energy use and performance-based minimum efficiency requirements for WICF. These test procedures and requirements were developed in 2011-2017; see Title 10 (Energy), Chapter II, Subchapter D, Part 431, Subpart R. According to the system classification shown in Figure 1, a WICF is a class ④ system.

The requirements on components include minimum insulation requirements and labelling requirements for panels, doors and refrigeration units; and maximum energy consumption (kWh/day) requirements for doors related to the surface area of the door and including electrical components associated with the door. Manufacturers of components must test, certify and label their components. Catalogues and marketing material must include the thermal resistance per unit area, R-value, (panels) or energy consumption value (doors).

Manufacturers and private labellers of components and complete WICF are subject to the regulations; installers of WICF are considered to be manufacturers of (complete) WICF. Manufacturers that only assemble complete WICF can rely on data of the component manufacturer to ensure component compliance, but must ensure that the completed WICF complies with the requirements. Manufacturers of both, components and complete WICF, are responsible for the compliance of both, the components and the complete WICF. Component manufacturers must certify each basic model and submit certification to the Compliance Certification Management System (CCMS) of DOE. The DOE Office of the General Counsel, Office of Enforcement enforces the requirements, and may request complete test data from the manufacturer, check certification information or conduct their own testing, following a modular approach.

Water pump unit: currently in the EU the (hydraulic part of) water pumps is regulated through Commission Regulation (EU) 547/2012. The products placed on the market have to meet a certain minimum efficiency, expressed as minimum efficiency index (MEI). Electric motors which are used to drive the water pump are regulated through Commission Regulation (EU) 2019/1781. In the revision of the water pump regulation, it is proposed to extend the scope to a ‘water pump unit, i.e. the hydraulic part (pump), the electric motor and the VSD (variable speed drive). Following the classification in Figure 1, this is a class ① system.

The proposed efficiency requirement for the water pump unit is using a metric of the energy efficiency index (EEI), as the ratio of the average measured electric power input (P_{avg}) and the reference power input (P_{ref}). P_{avg} is the weighted average of measured electric input power over four operating points, each weighted for its relative share in the flow-time. P_{ref} is the nominal input power of a fictitious water pump unit running at a nominal 100% load point, with a compliant water pump and an IE3 induction motor. Although the use of a VSD is not directly mandated, the proposed EEI requirement on the water pump is set at a level that can only be met with a VSD. The EU preparatory study for the review of the regulation estimates the savings from the adoption of this regulation at around 40 TWh/year in 2030 (Maya-Drysdale et al., 2018) - an order of magnitude larger than for water pumps alone (3.3 TWh/year). Applying a VSD ensures that load variations are matched by adjusting motor speed instead of throttling the motor. For fixed load applications adjusting the water pump to the required load point can be done via motor speed control instead of pump trimming.

The main issues to resolve are verification and enforcement. If a manufacturer is placing a water pump unit on the market, this unit has to comply with the requirements The verification by market surveillance authorities could be done in a laboratory using the black box approach as described in Table 3. However, water pump units that consist of a water pump, an electric motor and a VSD (each individually placed on the market) that are assembled, installed and put into service on location are also in the scope of the revised regulation. The main challenges are then to identify the actors that put water pump units into service (these may differ from the manufacturers of the parts), and to verify on location (some market surveillance authorities in EU Member States do not have the legal powers to visit installations).

Conclusions and recommendations

Substantial energy savings, in the order of 9 % of global energy use, provide a good motivation to address the challenges arising from extending energy efficiency product policy to regulate the performance of energy using systems. To refine this energy savings estimates more systems could be considered as more data becomes available, and the systems included could be investigated in more depth. Also of particular interest is quantifying the savings from new systems, and from those applying state of the art technologies, particularly for systems that could benefit from using advanced controls and automation, as these technologies continue to mature.

To develop regulatory approaches for systems, these need to consider the types of systems and their particular features. When the assembly of the system has a large impact on the efficiency (energy consumption and/or performance) the assembler should be (one of) the addressee(s) of the regulation, and the verification should focus on the quality of the assembly. An option to reduce the impact of the assembly on efficiency would be to regulate standardization of the assembly, by using standard interfaces or compatible parts; which could also be beneficial for optimizing assembly time and therefore costs. Finally this approach could also require assemblers to establish and maintain a quality management system.

In the case that the assembly has a small(er) impact on the efficiency, the addressee(s) could be the manufacturer of the system or the company that offers the system to a customer. This would cover a large variation of systems offered, assuming that all comply with the regulation. The manufacturer and/or the offering company should provide information on the efficiency of the system variations i.e., according to the relevant test method.

Table 6 summarizes the recommendations by mapping the regulatory solutions to the classification of systems as presented in Figure 1.

Table 6. Mapping systems and regulatory solutions

System class *(Refer to Figure 1)*	**Main elements of energy efficiency measures**		
	Scope and addressees	***Efficiency metrics and requirements***	***Verification and test methods***
①: Impact of assembly: small-medium; small number of parts	Manufacturers of (parts of) the system.	Efficiency of the parts and of the system.	Measurements on the parts of the system; modelling to provide results for the system (in a variety of usage conditions).
②: Impact of assembly: small-medium; large number of parts with a large % identical parts	Manufacturers of the parts.	Efficiency of the parts.	Measurements on the parts.
③: Impact of assembly small-medium; large number of parts with a small % identical parts	Manufacturers of the identical and/or critical[a] parts of the system. Assemblers/installers of the system.	Efficiency of the (identical/critical) parts. Efficiency of the system as assembled and installed.	Measurements on the (identical/critical) parts. Modelling to calculate system efficiency as assembled and installed.
④: Impact of assembly: large; small number of parts	Manufacturers of the parts. Assemblers/installers of the system.	Efficiency of the parts. Quality (control) of the assembly/installation.	Measurements on the parts. Check on the quality (control) of the assembly/installation.
⑤: Impact of assembly: large; large number of parts	Assemblers/installers of the system.	Quality (control) of the assembly/installation.	Check on the quality (control) of the assembly/installation.

[a] critical with regard to energy consumption of the system

In the case of systems in class ⑤, a final recommendation is to look at approaches used in buildings. If a quality control system is used for checking the assembly and installation of a system, this could be extended to take into account the owner that specifies the system.

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