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# The Economics of National Metrology Institutes: Valuing Measurement*

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**Abstract**

This paper estimates the economy-wide economic value of expanding metrological services using the Centro Nacional de Metrología (CENAM) of Mexico as a case study. The analysis models and quantifies how additional metrological service varieties affect the activity of secondary calibration laboratories, with an input-output simulation framework, which traces the resulting spillovers to aggregate output. Based on these estimates, the paper computes the Net Present Value (NPV) of alternative service expansion scenarios over a 20-year horizon and a 12% social discount rate. The results show that expanding CENAM's service catalogue generates substantial positive social returns. Starting from 587 services, the addition of one new variety yields an NPV of approximately USD 4.4 million, while an expansion of 100 varieties can justify investments of up to USD 321 million. Sensitivity analysis confirms that these conclusions are robust under conservative parameter assumptions.

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# I. Introduction

Together with standardization and accreditation, metrology constitutes one of the three fundamental pillars of a country's Quality Infrastructure (QI). Metrology, the science of measurement, ensures that measurements of time, length, mass, volume and other physical quantities are accurate, comparable, traceable and reliable across space and time. All modern measurement systems are anchored in the International System of Units (SI), which is globally coordinated by the International Bureau of Weights and Measures (BIPM). Without a trusted and coherent measurement system, modern production processes, technological innovation, regulatory enforcement, and international trade would simply not be possible.

In this context, National Metrology Institutes (NMIs) play a central role. NMIs are responsible for maintaining the highest-accuracy reference standards in a country and for ensuring traceability of all measurements to the SI. By doing so, they guarantee the uniformity and reliability of measurements carried out throughout the economy, an essential condition for firms' competitiveness, consumer protection, public health, and environmental stewardship. NMIs thus act as the technical anchor of national quality systems, enabling consistency across industries and international recognition of measurement results.

Metrology underpins quality, manufacturing, and innovation. Precision measurement ensures that products meet exact specifications, production processes remain stable and conformity with standards can be credibly demonstrated. In high-precision sectors such as aerospace, semiconductors, pharmaceuticals, and advanced manufacturing, small measurement errors can translate into large economic losses, safety risks, or market exclusion. More broadly, a well-functioning National Quality Infrastructure (NQI) (comprising metrology, standardization, and accreditation) allows firms to innovate, comply with regulations, integrate into global value chains, and access international markets on equal footing.

Every country maintains a designated institution charged with preserving its highest-accuracy standards: its National Metrology Institute. Examples include the National Institute of Standards and Technology (NIST, United States), the Physikalisch-Technische Bundesanstalt (PTB, Germany), the National Physical Laboratory (NPL, United Kingdom), the Instituto Nacional de Metrologia, Qualidade e Tecnologia (INMETRO, Brazil), and the Centro Nacional de Metrología (CENAM, Mexico). While institutional arrangements differ across countries, the mission of NMIs is common: to ensure accuracy, consistency, and international traceability, thereby linking every local measurement to the SI and to global metrological agreements.[5]

To fulfill this mission, NMIs maintain primary reference standards (i.e. objects or systems used to define, realize, and preserve units of measurement). These standards form the foundation of national measurement systems and are directly linked to the SI. In the case of Mexico, CENAM establishes the national standards for the seven base SI units and has additionally developed around 70 national standards across fields such as electromagnetism, frequency, force,

[5] In some countries, NMIs are directly embedded within the public administration and receive an explicit budget allocation, as is the case in the United States (National Institute of Standards and Technology, NIST), Germany (Physikalisch-Technische Bundesanstalt, PTB), Brazil (Instituto Nacional de Metrologia, Qualidades e Tecnologia, INMETRO), and Mexico (Centro Nacional de Metrología, CENAM). In other countries, where the custody of national standards has been fully or partially delegated to the private sector—such as the United Kingdom, Denmark, or Chile—public support for the establishment and maintenance of national standards is provided through long-term performance contracts with private entities, which include government oversight of the agreed tasks (Gonçalves et al., 2014).

pressure, flow, volume, acoustics, and photometry (PTB & CENAM, 2019). Beyond standards, NMIs also develop and certify reference materials (substances with well-characterized properties used to ensure accuracy, comparability, and quality control in chemical and analytical measurements).

The preservation of primary standards and the certification of reference materials are typically centralized in NMIs due to their large fixed costs and strong economies of scale (Gonçalves et al., 2014). These activities require highly specialized equipment, controlled environments, and long-term stability of materials, often complemented by backup standards to ensure continuity and risk mitigation. Once established, however, marginal costs of dissemination are relatively low. As a result, metrology exhibits characteristics of a natural monopoly.

Moreover, the benefits of accurate and traceable measurements are non-rival and non-excludable: once measurement results and traceability frameworks are established, all potential users benefit simultaneously, regardless of direct payment.[6] Measurement benefits are therefore largely non-appropriable, implying that social returns to metrology exceed private returns. For these reasons, the core functions of NMIs can be interpreted as the provision of fundamental public good, justifying sustained public support[7].

NMIs do not interact directly with all firms in the economy. Instead, they operate through a hierarchical measurement system supported by a network of secondary calibration and testing laboratories. These laboratories disseminate metrological traceability by calibrating firms' measuring instruments in accordance with the primary standards maintained by NMIs. Firms, in turn, operate their own working standards, validated through calibration certificates issued by these laboratories. Secondary laboratories may operate as third-party providers (independent firms offering calibration and testing services) or as first or second party laboratories embedded within firms or supply chains, depending on scale and operational needs.

Calibration thus takes the form of an uninterrupted chain of comparisons leading back to the primary standard. The further a laboratory or firm is from the realization of the SI unit (as defined through the BIPM system), the greater the associated measurement uncertainty.[8] While some firms with exceptionally stringent accuracy requirements may contract calibration services directly from NMIs, paying a premium to reduce uncertainty, most firms rely on the secondary laboratories network. This network acts as a powerful amplifier of the economic impact of NMIs, as its operations would not be possible without traceability to national primary standards.

Despite its central role in economic activity, measuring the economic impact of metrology remains challenging. Metrology generates economy-wide, long-chain effects that are difficult to isolate empirically. While numerous case studies document firm-level or sector-specific benefits, comprehensive estimates of economy-wide impacts are scarce, with only a few notable exceptions, such as studies conducted for the UK's National Physical Laboratory.

Against this backdrop, this paper develops a methodology to estimate the economy-wide impact of NMIs, using Mexico and CENAM as a case study. The analysis proceeds in two steps. First, a

[6] These users include other firms, final consumers, researchers and scientists, and the State itself, both as a consumer and as a regulator, among others.

[7] Despite being a natural monopoly, the fact that the marginal costs of metrological services are very low implies that wider dissemination and use is preferred to charging a monopolistic price for metrological services. This is the main reason why NMIs are normally subsidized organizations.

[8] Measurement uncertainty quantifies the quality of a measurement result and enables comparison with other results, reference values, standards, or regulatory requirements (Kellermann, 2019).

microeconomic model is calibrated to capture how the availability and diversity of metrological services affect the surplus and activity levels of secondary calibration and testing laboratories. Second, the estimated increase in laboratory output is fed into an input-output simulation framework developed by Mexico national statistics agency (INEGI, Instituto Nacional de Geografía y Estadística), which traces how this sectoral expansion propagates through the economy and affects aggregate output. Therefore, the paper integrates the partial-equilibrium estimates with this existing tool to obtain economy-wide results.

In the case of Mexico, secondary testing laboratories serve firms in 244 economic activities, with varying intensity. These laboratories constitute an economic activity comprising approximately 700 firms. By linking microeconomic effects at the laboratory level with economy-wide input–output linkages, the paper provides an integrated estimate of the contribution of metrology services to economic activity. Beyond its empirical application, the paper contributes to the literature by proposing an innovative framework to quantify the economic value of a fundamental public good (national metrology services) and by making explicit the transmission channels through which NMIs affect firms, sectors, and aggregate output.

In practice, the analysis draws on two main data sources. The first is CENAM's administrative panel, which covers all metrological services billed between 2019 and 2024 and includes, for each service, the number of transactions, the unit price, and a classification by metrological area. This dataset is used both to document the evolution of CENAM's service catalogue (which contracted from 665 varieties in 2019 to 587 in 2024) and to estimate the elasticity of substitution between service varieties, a key parameter of the partial-equilibrium model. The second data source is INEGI's 2018 input-output matrix at the six-digit NAICS level, which underlies the economy-wide propagation analysis. On the model side, secondary laboratories are assumed to have a CES technology over metrological service varieties, giving rise to an effect whereby a broader catalogue raises laboratory surplus. The elasticity of substitution is estimated at approximately 1.31, implying that restoring the catalogue to its 2019 level would increase laboratory surplus by around 33 percent and raise their output by approximately 8.6 percent. When this sectoral shock is fed into INEGI's input-output simulation tool, the estimated aggregate effect amounts to USD 35.8 million in additional GDP per year. Building on these results, the paper computes the Net Present Value (NPV) of expanding CENAM's catalogue under different scenarios (adding 1, 25, or 100 new varieties from alternative starting points) over a 20-year horizon at a 12 percent social discount rate. A Monte Carlo sensitivity analysis based on 5,000 replications confirms that the main conclusions are robust to uncertainty in the key parameters.

The remainder of the paper is structured as follows. Section II reviews the relevant literature. Section III presents the methodology and its application to Mexico. Section IV concludes.

## II. Related Literature

Metrology constitutes a fundamental pillar of the quality infrastructure, providing the scientific basis that ensures the traceability and reliability of measurements. Its contribution extends beyond firm competitiveness, improving overall quality of life through impacts on environmental protection, food safety, and human health, among other dimensions (Göthner and Rovira, 2011). By enabling the establishment of national standards, metrology facilitates firms’ integration into global value chains while protecting consumers and the environment.

At a general level, both foundational growth models (Lucas, 1988; Romer, 1990; Solow, 1956) and empirical evidence on infrastructure investment (Calderón, 2009; Calderón and Servén, 2004; Jung and Katz, 2023) underscore that expanding investment in enabling infrastructure is a necessary condition for scaling up essential services and advancing objectives related to economic and social development. In this context, strengthening metrology systems represents a critical, yet still under-measured component of productive infrastructure.

Despite its central role, the science of measurement has historically faced a paradox: the difficulty of measuring its own economic and welfare impacts. This challenge stems from the fact that the effects of metrology are both pervasive and highly specific. Metrology affects virtually all sectors of the economy, yet it does so in sector-specific ways that are difficult to aggregate into a single metric.

Several factors explain this complexity. First, the nature of demand for measurement varies substantially across sectors. For example, telecommunications network synchronization or satellite navigation requires definitions of the second with precision exceeding seventeen decimal places, levels of accuracy that are irrelevant for most other economic activities. Second, even within the same sector, measurement requirements can differ widely: in the automotive industry, fuel injector manufacturing requires microscopic tolerances, while door alignment allows errors on the order of millimeters.

A further challenge arises from the intrinsic heterogeneity of SI quantities themselves. A one-percent reduction in uncertainty in the realization of the second is not directly comparable to a similar reduction in voltage or length standards. Moreover, there is no universal or static notion of an "optimal" level of measurement accuracy, as metrological capabilities continuously evolve alongside technological progress and changing sectoral demands.

Finally, the outcomes of accurate measurement differ in nature and scope. The benefits of reducing food waste, lowering greenhouse gas emissions in plastics production, and enabling job creation through market access facilitated by precise measurements are fundamentally different, making aggregation particularly challenging.

Given these methodological difficulties, most empirical studies assessing the economic impact of metrology rely on case studies or evaluations of specific interventions, typically focusing on benefit–cost ratios.

A broad range of studies have documented positive economic effects from strengthening metrological services, including reductions in production losses, increases in firm productivity, and export expansion. For instance, Knapp (1997) estimates that each dollar invested by the Canadian Standards Council in periodic inspections saved an average of USD 11.4 through the reduction of measurement errors, rising to USD 28.7 in sectors where precision is critical.

Similarly, a KPMG (2001) evaluation of Canada's National Metrology Institute found that maintaining primary standards reduced transaction costs and preserved market trust, generating net annual benefits of CAD 18.9 million. In the United States, NIST's development of standardized reference materials for blood cholesterol measurement yielded a social return of 154% and a benefit–cost ratio of 4.47, through reduced production and transaction costs and fewer clinical errors (TASC Inc, 2000).

Evidence from the United Kingdom further illustrates these effects. Temple and Williams (2002) estimate that measurement-related R&D contributed the equivalent of 2% of GDP growth, with particularly strong impacts in high-technology sectors. Lambert (2010) finds that a one-point increase in a firm's metrological knowledge index is associated with an 8% increase in labor productivity, with effects concentrated in firms at the highest levels of metrological intensity, suggesting increasing returns to investment in measurement capabilities.

Lambert (2010) also documents a series of UK case studies showing highly favorable benefit–cost ratios, ranging from 12:1 to 25:1, across applications including product innovation, public revenue protection, scientific guidance, and telecommunications infrastructure.

In manufacturing, Savio et. al. (2016) show that integrating metrology into quality control and design processes enabled significant productivity gains and labor cost reductions in an automotive components manufacturer, while making clear that strict tolerance requirements could not be met without in-process metrology.

In Latin America, empirical evidence, though more limited, also points to substantial benefits. In Argentina, Saavedra (2011) estimates that the implementation of INTI's Legal Metrology Program prevented commercial disputes totaling nearly USD 968 million between 2003 and 2008, mainly in the grain sector, while fuel dispenser inspections prevented undue appropriations exceeding USD 13.5 million annually.

Studies compiled by Göthner and Rovira (2011) show that strengthening metrology and quality infrastructure can significantly boost exports. In Uruguay, dairy sector quality policies since the 1970s contributed to export growth of 8.9% between 1991 and 2009 and 18% between 2002 and 2009, driven by both product diversification and market expansion. Santo and Ferreira (2011) further link metrology and certification systems to a sustained 30% increase in productivity in Uruguay's dairy sector.

While the evidence reviewed above points to large and robust returns, it is important to emphasize that most estimates are partial, focusing on direct effects at the firm, project, or sectoral level. These studies generally do not capture the broader indirect effects and positive externalities that metrology generates along value chains, reinforcing its nature as a public good. Such indirect effects may substantially exceed the direct benefits typically measured (Swann, 2009).

As a result, the literature on economy-wide impacts of metrology remains limited and is still emerging. Recognizing this gap, recent work, particularly by the UK's National Physical Laboratory, has begun to develop new methodologies to estimate the aggregate economic impact of metrology. These include the use of input–output models to trace spillover effects across sectors (Fenelly, 2021; Dias and King, 2024), as well as firm-level econometric analyses exploring links between metrological investment, innovation, and productivity (Belmana Ltd., 2019; King and Renedo, 2020; Katanguru and King, 2024).

In this context, the framework developed in this paper aims to complement the existing evidence by providing a tractable, economy-wide approach to valuing metrological services. Rather than focusing on individual interventions, the framework links the expansion of metrological service offerings to aggregate economic benefits using a welfare-based metric that can be directly compared with investment costs. This allows for an ex-ante assessment of the economic justification for scaling up metrological capacity, helping bridge the gap between case-based evidence and policy-oriented cost–benefit analysis.

# III. Methodology

The main impact of expanding the coverage of metrological services provided by the National Metrology Institute (NMI) is an improvement in the services delivered by existing laboratories, reflected in greater service variety, higher quality, lower costs, and shorter turnaround times.

Although CENAM provides services directly to a limited number of firms with in-house laboratories (640 clients in 2024), its influence on the national and regional productive system operates primarily through third-party commercial laboratories (260 clients in 2024), whose measurements are traceable to CENAM's national standards. These laboratories act as intermediaries between primary metrology and the broader economy, transmitting improvements in metrological capacity to a wide range of productive sectors.

In this context, two main categories of beneficiaries of the NMI's primary metrology services can be identified. Direct beneficiaries are secondary calibration laboratories, which constitute the main source of demand for CENAM's metrological services. Indirect beneficiaries are firms and actors across different economic sectors that rely on these laboratories for calibration, testing, and measurement services.

The expansion of the NMI's catalogue of metrological services is neither immediate nor low-cost, as it requires the replacement and expansion of existing metrological systems, which in turn involves significant investments in highly specialized infrastructure and equipment. In particular, the introduction of new service varieties requires the acquisition of new metrological systems, whose procurement and commissioning entail complex public procurement processes, the involvement of specialized technical consultants, and supplier firms responsible for the installation, adjustment, and calibration of the equipment. According to CENAM's experts, in the case of Mexico this process may take between 6 and 24 months, depending on the technological complexity of each system. In addition, the NMI's technical and administrative teams must play an active role in defining, validating, and prioritizing service demand together with end users, reinforcing the capital-intensive, time-consuming, and capability-intensive nature of expanding metrological service provision.

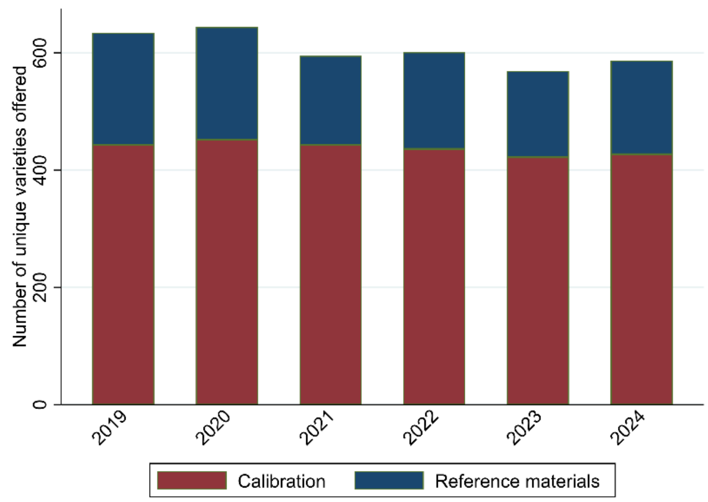
To quantify and monetize these benefits, the analysis adopts a two-step methodology aimed at estimating the economy-wide impact of CENAM's metrological services.

In the first step, a microeconomic, partial-equilibrium model of the market for CENAM's metrological services is developed. Supply is determined by the institution, while demand comes from secondary calibration laboratories. An increase in the number of service varieties offered by CENAM raises the surplus of calibration laboratories, which is reflected in higher levels of economic activity in this sector.

In the second step, the estimated increase in laboratory activity is used as an input to an economy-wide analysis. Specifically, an input–output framework is employed to trace how the project-induced expansion in laboratory activity propagates through the Mexican economy, affecting value added across sectors and ultimately GDP. This approach makes it possible to capture both the direct effects on calibration laboratories and the indirect effects transmitted along production chains.

For these matters, we have used both CENAM administrative data and INEGI's Input-Output Matrix publicly available. CENAM's administrative yearly panel data covers the period from 2019 until 2024 of the offered services that were demanded by secondary laboratories and final users including the name of the service (with variables indicating broader product categories), the number of billed services, and their price. As is shown in Figure 1, the number of varieties offered has decreased since 2019.

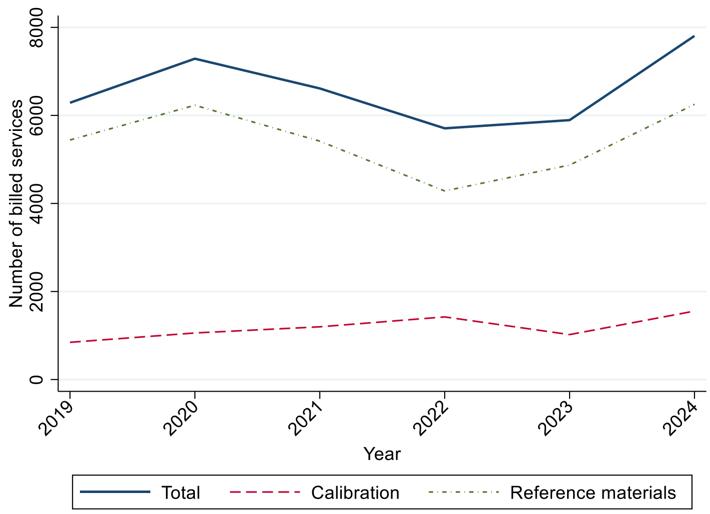
**Figure 1: Evolution of the number of unique varieties offered**




Source: Authors' elaboration based on CENAM.

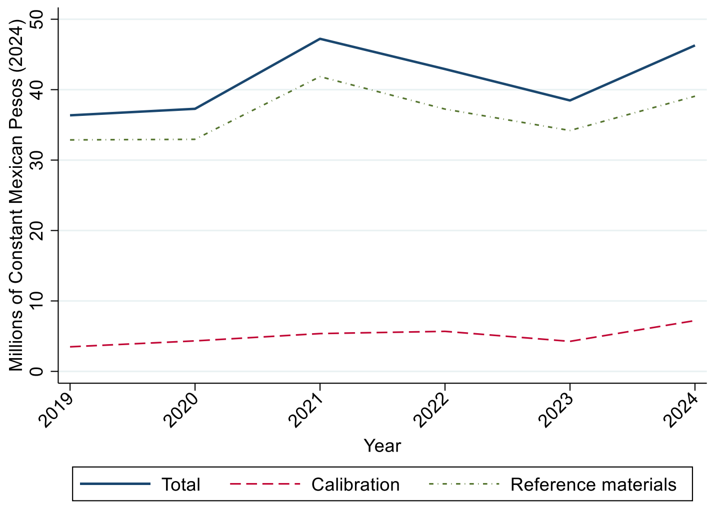
Nonetheless, even as the number of offered varieties has decreased, the demand for metrological services has increased, as documented both by evolution of the billed quantities and the total amount that CENAM has received as income for providing these services as shown in Figure 2 and Figure 3. Together, these results indicate that new services are widely used across firms and there may be an unsatisfied demand for metrological services both for certifications and reference materials.

**Figure 2: Evolution of the number of metrological services billed**




Source: Authors' elaboration based on CENAM.

**Figure 3: Evolution of CENAM's revenues from metrological services provided**




Source: CENAM.

Of the offered varieties, the most billed ones for the year 2024 are presented in Table 1. The most billed reference material service is the interferometric gauge block set of 88 or more pieces (823 services), a fundamental tool for dimensional calibration in precision manufacturing. This is followed by the calibration of KOBA/ITS graduated rulers per 100 mm (462 services), also linked to dimensional metrology, and the calibration of high-accuracy AC voltage meters against a thermal voltage converter (TVC, 357 services), essential for electrical laboratories. Fourth is the calibration of high-precision multifunction calibrators for alternating voltage (268 services), and fifth is the calibration of high-accuracy digital multimeters for electrical resistance (243 services), both critical for the electronics and instrumentation industries.

Regarding the calibration services, the most billed services are the certification of phosphate salts (disodium phosphate and monobasic potassium phosphate), compounds widely used as reference materials for calibrating pH measurement instruments, reflecting strong and recurring demand from analytical and quality control laboratories (101 services). This is followed by the spectrometric determination of lead (78 services), relevant for environmental monitoring and food safety, and the certification of water density at 20°C (74 services), a fundamental quantity in physical and chemical metrology. Tied in fourth place is the certification of the viscosity value of a reference liquid (74 services), used to calibrate viscometers in industries such as petrochemicals and pharmaceuticals. Rounding out the top 5 is the certification of the density of a polyalphaolefin (65 services), a synthetic oil commonly used as a standard liquid in density measurement instruments. Overall, the top calibration and reference material services represent more than 30% of the total services billed in 2024 but less than 15% of total sales in Mexican pesos.

To make these benefits more tangible, the Appendix 1 presents two case studies of new metrological services with documented positive economic impacts, illustrating how investment in metrological infrastructure translates into concrete gains for the productive sector.

**Table 1: Top 5 CENAM's most billed metrological services by type in 2024**

| Ranking | Calibration | | Reference materials | |
|---|---|---|---|---|
| | *Service* | *Freq.* | *Service* | *Freq.* |
| 1st | pH-Certified Disodium Phosphate and Monobasic Potassium Phosphate Salts | 101 | Interferometric pattern blocks consisting of 88 or more pieces. | 823 |
| 2nd | Spectrometric determination of lead | 78 | Calibration of KOBA/ITS Graduated Ruler per 100 mm | 462 |
| 3rd | Liquid, density certified (Water, average density at 20 °C, 998 kg/m³) | 74 | Calibration of high-accuracy AC voltage meters vs. TVC. | 357 |
| 4th | Certification of the viscosity value of the reference liquid at an additional temperature | 74 | Calibration of a high-precision multifunction calibrator. Measured quantity: alternating voltage. | 268 |
| 5th | Liquid, density certified (polyalphaolefin, average density at 20 °C, 794 kg/m³) 100 ml | 65 | Calibration of high-accuracy digital multimeters. Measurable property: Electrical resistance. | 243 |

Source: CENAM.

## III.1 Brief description of the Mexican Metrological market

The market for metrological services in Mexico is organized around three main economic agents: the National Metrology Institute (CENAM), secondary calibration and testing laboratories, and firms across the productive sector. Each plays a distinct role in the dissemination of metrological traceability throughout the economy.

At the apex of this system sits CENAM, Mexico's designated National Metrology Institute, operating under the Ministry of Economy. CENAM maintains the country's primary reference standards for the seven SI base units, as well as approximately 70 additional national standards spanning electromagnetism, frequency, force, pressure, flow, volume, acoustics, and photometry. It also develops and certifies reference materials used in chemical and analytical measurements. CENAM sets its service tariffs annually on the basis of estimated provision costs, ensuring that prices remain close to marginal cost and consistent with its role as a publicly subsidized institution. In 2024, CENAM served approximately 900 clients directly, of which 640 were firms or institutions with in-house measurement needs and 260 were third-party commercial laboratories.

Secondary calibration and testing laboratories constitute the primary channel through which CENAM's services reach the broader economy. These laboratories acquire metrological services from CENAM to ensure that their own measurement instruments are traceable to national primary standards, and in turn issue calibration certificates to their clients. They may operate as independent third-party providers or as first- or second-party laboratories embedded within firms or supply chains. As of 2025, Mexico's National Directory of Economic Units (DENUE) recorded approximately 790 such laboratories, classified under NAICS 541380, the vast majority of which employ up to 50 workers. Their number has remained broadly stagnant over the past decade, with a mild declining trend. These laboratories sell intermediate services to 244 different six-digit NAICS activities, with the largest shares concentrated in pharmaceutical manufacturing, automobile assembly, oil and gas drilling, and construction.

Firms across the productive sector are the indirect beneficiaries of this system. They rely on secondary laboratories to calibrate their working measurement instruments, validate production processes, and demonstrate conformity with quality and safety standards. This need is particularly acute in sectors where precision is critical (such as pharmaceuticals, automotive manufacturing, and energy) where small measurement errors can translate into large economic losses, product recalls, or market exclusion. While some firms with exceptionally stringent requirements contract calibration services directly from CENAM, the overwhelming majority of productive activity is served through the secondary laboratory network. In this sense, secondary laboratories act as a powerful amplifier of CENAM's economic influence, and their activity would not be possible without traceable access to national primary standards.

## III.2 Microeconomic Model

This subsection develops a partial-equilibrium model with microeconomic foundations to quantify the impact of changes in the metrological services provided by Mexico's National Metrology Institute (NMI) on the welfare of users in the market in which CENAM operates, namely the market for metrological services supplied to secondary laboratories. The analysis is based on a technology structure with "love for variety" and focuses specifically on the welfare effects associated with an expansion in the range of services offered by the NMI.

On the supply side, it is assumed that the NMI offers a catalogue of $i = 1 \ldots N$ metrological services, with prices $p_i$ set on the basis of their provision costs $c_i$. CENAM sets tariffs annually based on estimated service provision costs, so that prices equal costs and producer surplus is zero. Total surplus therefore equals the surplus of secondary laboratories.

On the other hand, demand for metrological services is determined by secondary calibration laboratories, and the quantities traded are determined by their demand for each variety. Metrological varieties are intermediate inputs in private laboratories' production process.

Indeed, private laboratories are assumed to have a short-run production function given by:

$$Y(\bar{L}, Q) = \bar{L}^{1-\alpha} Q^{\alpha} \tag{1}$$

where $\alpha \in (0,1)$ and $\bar{L}$ represents a composite of fixed production factors such as capital and labor. Since $\bar{L}$ can be normalized to 1, the production function simplifies to:

$$Y(Q) = Q^{\alpha} \; . \tag{2}$$

Here $Q$ is a CES aggregate of metrological inputs demanded by laboratories, defined as

$$Q = \left[\int_0^N q_i^{\frac{(\sigma-1)}{\sigma}} di\right]^{\frac{\sigma}{(\sigma-1)}},$$

where $N$ denotes the total number of metrological service varieties and $\sigma$ is the elasticity of substitution between varieties.

Solving the firm's cost-minimization problem yields the derived demand for each variety $q_i^d$ :

$$q_i^d = Q\left(\frac{p_i}{P}\right)^{-\sigma} = \frac{E}{P}\left(\frac{p_i}{P}\right)^{-\sigma} \tag{3}$$

where $p_i$ denotes the price of each variety, $E = PQ$ represents the total cost of the metrological input, and $P$ is an aggregate price index representing the unit cost of production, defined as $P = \left[\int_0^N {p_i}^{1-\sigma}\, di\right]^{\frac{1}{(1-\sigma)}}$.

Assuming symmetry in prices across varieties (so that for every variety $c_i = c$), the aggregate price index becomes:

$$P = \left[\int_0^N c^{1-\sigma}\, di\right]^{\frac{1}{(1-\sigma)}} = cN^{\frac{1}{(1-\sigma)}}, \tag{4}$$

and the derived demand for each variety simplifies to

$$q_i^d = Q\left(\frac{c}{cN^{\frac{1}{(1-\sigma)}}}\right)^{-\sigma} = QN^{\frac{\sigma}{(1-\sigma)}} \tag{5}$$

Thereafter,

it follows that in equilibrium, the aggregate cost function of secondary laboratories is

$$\Gamma\big(Q, P(c,N)\big) = \Gamma(Q,c,N) = QcN^{\frac{1}{(1-\sigma)}} \tag{6}$$

For each level of $Q$ chosen by laboratories in their cost-minimization problem. Since excess demand is ruled out, equilibrium occurs in the perfectly elastic segment of supply. As a result, producer surplus (CENAM) is zero—prices equal costs—an assumption consistent with the institutional setting in which the NMI sets tariffs annually based on estimated service provision costs. Total surplus is therefore equal to the surplus of laboratories $(LS)$.

Moreover, under standard assumptions, changes in laboratory surplus lie between compensating and equivalent variation.[9] For instance, when prices fall, compensating variation is smaller than the change in labs' surplus. In this context, a suitable approximation to compensating variation $\widetilde{CV}$ is the following money-metric welfare measure:

$$\widetilde{CV} = \Gamma\big(Q_0, P_0(c,N_0)\big) - \Gamma\big(Q_0, P_1(c,N_1)\big)$$

Here, $\widetilde{CV}$ captures the reduction in input costs required for laboratories to attain the same level of effective metrological services following a decrease in the aggregate price index. As such, it provides a lower-bound measure of the economic gains from variety expansion. Therefore, it captures the secondary laboratories' willingness to pay for an expansion in metrological varieties that reduces the overall price index. Using the cost function (6), the compensating variation $\widetilde{CV}$ can be written as

$$\widetilde{CV} = Q_0 c\left(N_0^{\frac{1}{(1-\sigma)}} - N_1^{\frac{1}{(1-\sigma)}}\right) \tag{7}$$

This measure holds initial aggregate consumption fixed at $Q_0$ and computes how much the representative laboratory would need to spend under the new number of varieties to consume the same aggregate quantity as before. As such, it provides a lower-bound measure of the economic gains from variety expansion. That is, when input costs fall, laboratories can optimally adjust their input choices and production scale, leading to additional gains beyond those

[9] The assumptions required are that goods are normal and that preferences are continuous, complete, transitive, monotonic, and convex.

captured by this fixed-quantity comparison. Because compensating variation does not account for these behavioral responses, it provides a lower-bound estimate of the total increase in laboratory surplus.

Thus, since the change in laboratory surplus is greater than or equal to compensating variation, the percentage increase in laboratory surplus resulting from an expansion in the number of varieties satisfies:

$$\Delta\%LS \geq \Delta\%\widetilde{CV} = \frac{(Q_0 P_0 - Q_0 P_1)}{Q_0 P_0} \times 100 = \frac{\left[ N_0^{\frac{1}{(1-\sigma)}} - N_1^{\frac{1}{(1-\sigma)}} \right]}{N_0^{\frac{1}{(1-\sigma)}}} \times 100 \quad (8)$$

This expression requires only information on $N$ and $\sigma$, which can be obtained from CENAM's administrative data on prices and quantities sold for services in its catalogue. In the rest of the analysis, we will assume that equation (8) holds with equality and refer to it as a percent increase in labs' surplus.

For illustrative purposes the change in the compensating variation can be used to have an approximation of the change in the laboratories' surplus following Feenstra (2010), who shows that $\Delta LS = \left(\frac{E}{\sigma-1}\right) \times \Delta\%\widetilde{CV}$. Nonetheless, this measure should be interpreted with caution, as it provides an approximation of welfare gains and is not used for the input–output simulations of the next sub-section, which depend exclusively on the proportional change in the metrological input cost derived above.

Specifically, in 2024 CENAM recorded demand for 587 varieties of calibration services and reference materials. If the number of varieties were to return to its 2019 level, the relevant values would be:

$N_0 = 587$: number of metrological services offered in 2024.

$N_1 = 665$ number of metrological services if restored to the 2019 level.[10]

The elasticity of substitution $\sigma$ can be estimated using CENAM's data on prices and quantities of metrological services. That is, from the laboratory optimum, $q_i^d = Q\left(\frac{p_i}{P}\right)^{-\sigma}$, which implies $\frac{q_i^d}{Q} = \left(\frac{p_i}{P}\right)^{-\sigma}$, and taking natural logarithms yields:

$$\ln\left(\frac{q_i^d}{Q}\right) = -\sigma \ln\left(\frac{p_i}{P}\right) \quad (9)$$

Following Selvanathan et al. (2024), aggregate quantities $Q$ and the price index $P$ are proxied by total quantities demanded and the average price of each variety. The dataset includes information on prices and quantities demanded for all calibration services and reference materials in CENAM's catalogue between 2019 and 2024. Each service belongs to one of 15

[10] The reduction in the number of metrological service varieties offered by CENAM between 2019 and 2024 reflects a prolonged period of underinvestment associated with declining real public budget allocations to the institution (CENAM, 2024). As documented in Gonzales et al. (2025), sustained budgetary constraints limited CENAM's ability to renew equipment, maintain controlled laboratory conditions, and develop new services, leading to the withdrawal of existing services and an erosion of its service portfolio. This contraction should therefore be interpreted as a supply-side constraint driven by fiscal underinvestment, rather than by a decline in underlying demand for metrological services.

metrological divisions (departments). Equation (9) is estimated under alternative fixed-effects specifications, ranging from metrological-division fixed effects to division-by-year fixed effects.[11]

Table 2 reports the estimated values of $\sigma$ under these specifications.[12] The estimates range between 1.31 and 1.34 in absolute values. Based on equation (8) and the values of $N_0$ and $N_1$ proposed above, these values of $\sigma$ imply an increase in laboratory surplus of approximately 33 percent per year. An advantage of this methodological approach is that changes in the catalogue size alone allow for an approximation of the resulting increase in secondary laboratories' economic activity. This increase in activity constitutes the input for the aggregate impact analysis based on the input–output matrix presented in the following subsection.

**Table 2: Elasticity of substitution between metrological services varieties**

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| $\ln(pi/P)$ | -1.317*** | -1.328*** | -1.289*** | -1.301*** |
| | [0.219] | [0.228] | [0.256] | [0.226] |
| ***Fixed effects*** | | | | |
| Metrological Division | X | X | | |
| Year | | X | X | |
| Metrological Division-Year | | | | X |
| | | | | |
| Observations | 2,026 | 2,026 | 2,026 | 2,026 |
| R-squared | 0.370 | 0.372 | 0.264 | 0.397 |

Source: Authors' elaboration based on CENAM data. Note: "Area" refers to the metrological systems to which CENAM's different services belong. Standard errors clustered at the service level are reported in brackets. *** p<0.01, ** p<0.05, * p<0.1

As shown in Table 3 below, laboratory welfare increases as CENAM offers a larger number of service varieties and decreases as the elasticity of substitution between services rises. For the average value of sigma across specifications (1.31), laboratory welfare is estimated to increase by at least 33%[13].

[11] Using a different specification, King and Renedo (2020) employ data for the United Kingdom's National Metrology Institute and find a price elasticity of demand for metrological services greater than one in absolute value. They also estimate a distance elasticity of demand of −0.48. This result is used to assess the impact on demand of eliminating a local metrological service and having to procure it abroad instead.

[12] As prices and quantities are simultaneously determined, the estimated coefficients might be biased and inconsistent due to endogeneity. However, this potential limitation should be also qualified by considering that CENAM's pricing strategy is based on setting service tariffs annually according to estimated provision costs, ensuring that prices remain close to marginal costs and consistent with its role as publicly subsidized institution. So, giving this pricing behavior, we consider that the feedback from demand into price should be minimum.

[13] Using the expression $\Delta LS = \left(\frac{E}{\sigma-1}\right) \times \Delta\%\widetilde{CV}$ derived by Feenstra (2010), and approximating $E$ by CENAM's revenue from the sale of metrological services in 2024 (USD 6.5 million), this would imply that laboratories' surplus would increase by USD 6.9 million.

**Table 3. Change in Laboratory Surplus Following an Increase in the Number of Varieties Offered by CENAM**

| Sigma | $\Delta\%\ LS$ |
|---|---|
| 1.29 | 35.0% |
| 1.30 | 34.0% |
| 1.31 | 33.1% |
| 1.32 | 32.3% |
| 1.33 | 31.5% |

Source: Authors' elaboration based on CENAM data. Note: The initial number of varieties is taken as the 2024 level (587), and the final number of varieties is 665 (the value for 2019).

Once the proportional increase in laboratories' profits has been estimated, it becomes relevant to quantify how much of this increase is translated into sectoral output, a variable that was previously assumed constant to compute the welfare increase of laboratories. To do so, it is assumed that the output–profit elasticity (denoted by $\eta_{y,\pi}$) can be approximated by the output–markup elasticity ($\eta_{y,m}$). Although this constitutes an empirical simplification, it is motivated by the fact that the markup ($m$), defined as $m = \frac{P}{c} - 1$, is a measure of profit per unit of output. Accordingly, the elasticity of output with respect to markups is used as a proxy for the elasticity of output with respect to profits. An advantage of this approach is that $\eta_{y,m}$ has been extensively estimated in the empirical literature. De Loecker et al. (2019), using firms' market values as a proxy for output, find that $\eta_{y,m}$ ranges between 0.27 and 0.71, with the lower value preferred as it incorporates firm and year fixed effects. Using a similar methodology, Rivera-Padilla (2023) estimates that in Mexico $\eta_{y,m}$ lies between 0.15 and 0.37, depending on the specification.

Alternatively, $\eta_{y,m}$ can be estimated as the product of the investment–markup elasticity and the output–capital elasticity.[14] This alternative approach is useful because it explicitly identifies a channel through which increases in private laboratories' profits may translate into higher economic output: higher profit margins lead to increased investment, which in turn raises output. Heresi (2024) finds a positive and statistically significant correlation between markups and investment in the subsequent period. At the global level, the author estimates that firms at the 50th percentile of the markup distribution exhibit an investment–markup elasticity ranging between 0.86 and 1.21. The same average measure for six Latin American countries, including Mexico, lies between 1.23 and 1.24.[15] Using the Total Factor Productivity series published by INEGI, it is possible to estimate that in SCIAN sector 54 (professional, scientific, and technical services), the capital share in output, which serves as an estimate of the output–capital elasticity under a Cobb–Douglas technology, is approximately 53%.[16] Under this alternative approach, the

[14] $\eta_{y,m} = \eta_{I,m}\eta_{y,K}$ assuming, as is standard, that investment translates one-to-one into capital in the subsequent period.

[15] The higher values found for these elasticities relative to the output–markup elasticity may be due to the fact that investment is more sensitive to expected profitability—which increases with the markup—whereas output also depends on demand conditions, relative prices, and technological constraints, all of which tend to be more binding in capital-intensive sectors. In addition, these differences may reflect liquidity constraints, insofar as a higher markup increases firms' cash flow in a context where the Modigliani–Miller theorem does not hold.

[16] https://www.inegi.org.mx/programas/ptf/2018/#datos_abiertos

lower bound for $\eta_{y,m}$ is therefore 0.46 (0.86 × 0.53), while the upper bound is 0.63 (1.24 × 0.53). These results are reported in Table 4.

**Table 4: Estimations of the Output-Profit Elasticity $\eta_{y,m}$**

| Country | Min | Max | Reference |
|---|---|---|---|
| United States | 0.27 | 0.71 | De Loecker et al. (2019) |
| Mexico | 0.15 | 0.37 | Rivera-Padilla (2023) |
| Mexico | 0.46 | 0.63 | Heresi (2024), INEGI (2025) |

Source: Authors' elaboration based on the references mentioned in the table.

To summarize, the main result of the partial-equilibrium approach is the increase in secondary laboratories output (denoted by $\Delta\%v_k$) resulting from an increase in the number of varieties offered by CENAM, which from equation (8) and the discussion above can be written as

$$\Delta\%v_k = \frac{\left[N_0^{\frac{1}{(1-\sigma)}} - N_1^{\frac{1}{(1-\sigma)}}\right]}{N_0^{\frac{1}{(1-\sigma)}}} \times \eta_{y,m} \times 100. \tag{10}$$

This approach has a number of limitations besides the assumptions of the model. First, it ignores the externalities associated with the public-good nature of metrology since prices do not reflect its full social value, which are not addressed in this analysis and therefore remain outside the scope of the cost–benefit assessment. Second, it abstracts from the multiplier effect of metrology on economic activity, an aspect that is addressed in the following subsection.

### III.3 Input-output Model

In the previous subsection we obtained a measure of the laboratories sector output increase $\Delta\%v_k$ resulting from the expansion of CENAM's metrological services. Following an input–output (I–O) analysis, we assess how this increase in activity in one sector (secondary laboratories) propagates through the economy, affecting other sectors and gross domestic product (GDP). To this end, we use Mexico's input–output matrix (I–O matrix), which captures all economic transactions among productive sectors at the six-digit level of the North American Industry Classification System (NAICS).

In this framework, the increase in calibration activity is interpreted as a positive supply shock to the laboratories sector. This shock raises the sector's effective output capacity, which is then transmitted to the rest of the economy according to its pattern of intersectoral sales. In particular, under a supply-driven (Ghosh, 1958) I–O model, the additional output of the laboratories sector is allocated across downstream sectors in proportion to the distribution of its sales (i.e., along the rows of the I–O matrix). As a result, sectors that rely more intensively on calibration services experience a larger expansion in activity, which in turn propagates further through their own linkages with other sectors.

This mechanism implies that the initial increase in the laboratories sector generates a cascade of indirect effects across the production network, ultimately affecting aggregate output (GDP). The underlying assumptions are that supply shocks are fully transmitted (perfect pass-through), that technical coefficients remain fixed, and that there are no binding demand constraints.

This is exactly the model developed for Mexico by the National Institute of Statistics and Geography (INEGI) to estimate the aggregate impact of a sectoral supply shock.[17] In simple terms the model estimates an increase in total GDP resulting from a supply shock $\Delta v_k$ in a sector $k$ as

$$\Delta\% GDP = \Delta\% v_k \times m_k \tag{11}$$

The parameter $m_k$ is an output multiplier, whose derivation in the context of a Ghosh model is presented in the Appendix 2.

The NAICS code that encompasses the CENAM's direct beneficiaries is 541380 (Testing Laboratories). To a lesser extent, activity code 811219 (Repair and maintenance of other electronic and precision equipment) could also be considered; however, it is excluded here in order to adopt a conservative strategy. [18]

Based on the INEGI's model to estimate the aggregate impact of a sectoral supply shock, it is found that, for each one percentage point increase in the activity of secondary laboratories, Mexico's GDP increases by USD 4.156 million per year (2018 data expressed in 2025 prices). By using the estimated increase in the activity of testing laboratories resulting from the expansion of metrological services provided by CENAM, derived from the partial-equilibrium analysis in the previous subsection, it is therefore possible to estimate the economy-wide impact of an investment program in metrological infrastructure.

To illustrate the multiplier effect of secondary laboratories' activity, it is useful to consider the sectors to which they sell their services. According to Mexico's National Directory of Economic Units (DENUE), as of 2025 there were 790 testing laboratories in the country, the vast majority of which employ up to 50 workers. The number of laboratories has remained stagnant over the past decade and has shown a declining trend, as illustrated in Figure 4.

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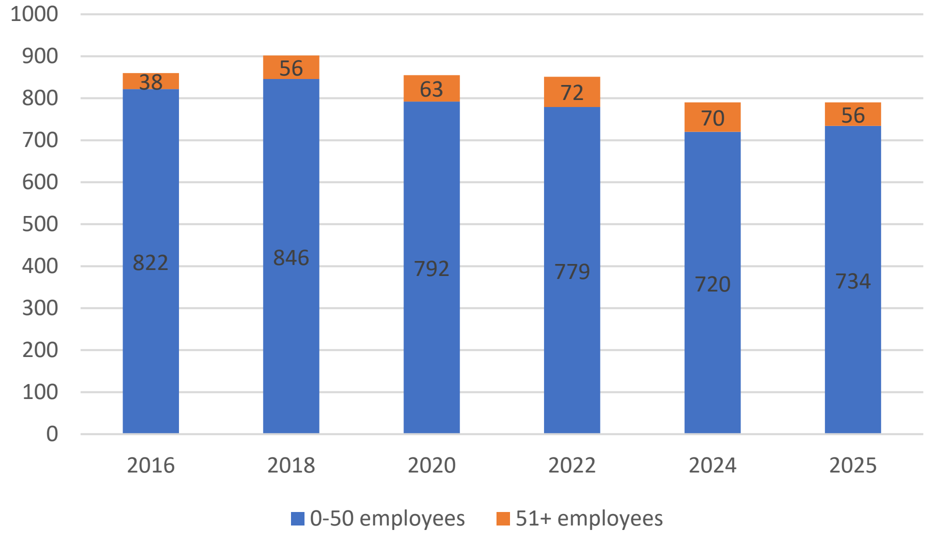
[17] For more details on INEGI's Sectoral Impact Simulation Model see https://www.inegi.org.mx/app/simuladormip18/

[18] NAICS 541380 includes economic units primarily engaged in providing product or substance testing, instrument calibration, reference materials, and product certification services. The tests performed may be chemical, physical, or similar in nature, including acoustic, optical, electrical and electronic, destructive and non-destructive, force and pressure, flow and volume, biological, calibration, and thermal testing. The link between NAICS 811219 and metrology is less direct, as it includes "economic units primarily engaged in the repair and maintenance of computers and peripherals, photocopiers, electronic typewriters, calculators, scales, balances, microscopes, medical, navigation and communication equipment, and other electronic and precision equipment." However, a review of firms listed in Mexico's National Directory of Economic Units (DENUE, https://www.inegi.org.mx/app/mapa/denue/default.aspx) identifies companies within this category that do provide metrological services.

**Figure 4. Testing Laboratories (NAICS 541380)**




Source: Authors' elaboration based on DENUE, INEGI.

Based on the input–output matrix, this sector sells its output to 244 other six-digit NAICS activities. Table 5 below presents the 30 activities with the largest shares of intermediate sales of NAICS 541380. Together, these activities account for 91% of testing laboratories' sales and are primarily linked to the pharmaceutical, automotive, construction, energy, and mining industries. It is worth noting that all activity in NAICS 541380 is concentrated in intermediate sales and that the sector does not have final demand in the form of private or public consumption, investment, or net exports.

Other studies adopt a similar input–output approach. Rodrigues Filho et al. (2020) estimate the potential aggregate impact of different measurement errors on the traded quantities of Brazil's main primary export products. Dias and King (2024), in turn, analyze the potential impacts of metrology across different economic sectors in the United Kingdom. To do so, they consider several sectors that use metrological services provided by the National Physical Laboratory (NPL), the UK's NMI. Specifically, they include the following calibration-related sectors: manufacturing of computer, electronic, and optical products; architectural and engineering activities; technical testing and analysis; and other professional, scientific, and technical activities.[19] By contrast, the present study considers only the testing laboratories activity as the channel through which the effects of the calibration chain propagate to the rest of the productive sectors. As a result, the estimates presented here can be interpreted as a lower-bound estimate of the impact of metrology on economic activity.

[19] Dias and King (2024) note that, while this selection of sectors represents those that transmit calibration services along the calibration chain, its definition is inherently subjective.

**Table 5. Sectoral Distribution of Intermediate Sales (NAICS 541380)**

| NAICS | Description | % Sales |
|---|---|---|
| 325412 | Manufacture of pharmaceutical preparations | 30.8% |
| 336110 | Manufacture of automobiles and light trucks | 19.8% |
| 213111 | Drilling of oil and gas wells | 9.5% |
| 336370 | Manufacture of stamped metal parts for motor vehicles | 7.1% |
| 236221 | Construction of commercial and service buildings, except supervision | 6.0% |
| 237312 | Construction of highways, bridges, and similar infrastructure | 3.0% |
| 236112 | Construction of multifamily residential buildings | 2.0% |
| 336330 | Manufacture of steering and suspension system parts for motor vehicles | 1.8% |
| 431110 | Wholesale trade of groceries | 1.4% |
| 336390 | Manufacture of other motor vehicle parts | 1.1% |
| 212222 | Silver mining | 0.9% |
| 331220 | Manufacture of other iron and steel products | 0.9% |
| 323119 | Printing of continuous forms and other printed materials | 0.8% |
| 322210 | Manufacture of paperboard containers | 0.5% |
| 331112 | Manufacture of primary metal shapes and ferroalloys | 0.5% |
| 332310 | Manufacture of metal structures | 0.5% |
| 336510 | Manufacture of railroad equipment | 0.5% |
| 336360 | Manufacture of seats and interior accessories for motor vehicles | 0.5% |
| 112120 | Cattle farming for milk production | 0.4% |
| 332710 | Machining of parts for general machinery and equipment | 0.4% |
| 541690 | Other scientific and technical consulting services | 0.4% |
| 541711 | Private scientific research and development services in natural and exact | 0.3% |
| 111339 | Cultivation of other non-citrus fruit and nut trees | 0.3% |
| 237993 | Construction of electric power and railway transportation infrastructure | 0.3% |
| 334210 | Manufacture of telephone equipment | 0.3% |
| 112211 | Hog farming | 0.2% |
| 332211 | Manufacture of non-powered metal hand tools | 0.2% |
| 931610 | Administrative activities of social welfare institutions | 0.2% |
| 336310 | Manufacture of engines and engine parts for motor vehicles | 0.2% |
| 332810 | Metal coating and finishing services | 0.2% |

Source: Authors’ elaboration based on the Input–Output Matrix, INEGI.

## III.4 Integrating the Two Approaches

This subsection brings together the two analytical components developed in the previous sections in order to quantify the economy-wide impact of expanding metrological services. Specifically, it combines the partial-equilibrium valuation of gains accruing to secondary calibration laboratories with an input–output framework that captures how these gains propagate through the production network. The objective is to translate improvements in laboratories’ economic performance—stemming from an expanded catalogue of metrological services—into an estimate of aggregate effects on economic activity, measured by the GDP.

The analysis proceeds in two steps. First, the partial-equilibrium model is used to estimate the increase in laboratory surplus resulting from the supply-side expansion of metrological services.

Second, the resulting increase in laboratories' activity is treated as a sectoral supply shock and mapped into the input–output matrix to assess its spillover effects across the economy. Table 6 summarizes the parameters used in this integrated analysis, which were discussed in the preceding sections. Specifically, using an elasticity of substitution across varieties of 1.31, the number of service varieties with and without the two scenarios, and the intermediate value of the output–markup elasticity for Mexico of 0.26, the partial-equilibrium model yields an estimated increase in secondary laboratories' surplus of 33.1%. Based on equation (10) this translates into an 8.6% increase in the activity of secondary laboratories classified under NAICS 541380. Using the outputs multipliers derived by INEGI presented in equation (11), this supply shock to testing laboratories results in an annual increase in GDP of USD 35.8 million.

**Table 6. Key Parameters and Main Result**

| Variable | |
|---|---|
| Number of varieties without the project | 587 |
| Number of varieties with the project | 665 |
| Elasticity of substitution between varieties | 1.31 |
| Increase in Laboratory Surplus (%) | 33.1 |
| Output–markup elasticity | 0.26 |
| GDP generated per 1 percentage point increase in NAICS/SCIAN 541380 (USD million) | 4.156 |
| **Total increase in GDP from the expansion of metrological services (USD million)** | **35.8** |

Source: Authors' elaboration based on Tables 1, 2, 3, and Figure 1.

Summarizing, the I-O framework is used to trace the economy-wide consequences of the supply-side expansion in metrological services described in the previous subsection. The transmission mechanism operates as follows. An increase in the number of metrological service varieties offered by CENAM reduces the aggregate price index faced by secondary laboratories, raising their surplus and, through the output-profit elasticity discussed above, their level of output. This increase in laboratory output, estimated from the partial-equilibrium model, is treated as an exogenous sectoral supply shock to NAICS 541380 (Testing Laboratories) and fed into INEGI's sectoral impact simulation model. The simulation tool, which is built on Mexico's 2018 I-O matrix at the six-digit NAICS level, then computes how this initial expansion propagates through the 244 sectors that purchase intermediate services from testing laboratories, ultimately yielding an estimate of the aggregate effect on GDP. In this way, the partial-equilibrium and I-O components of the analysis are linked sequentially: the former determines the magnitude of the shock to laboratory activity, and the latter translates that shock into economy-wide output effects.

## III.5 Economic Value of Expanding Metrological Services

The exercise presented above considers a hypothetical scenario in which the number of metrological services offered by CENAM returns to its 2019 levels, which were higher than those observed in 2024. This section examines different starting points (i.e., initial numbers of available metrological services) and alternative expansion scenarios in order to quantify the net present value (NPV) of such expansions. These NPVs provide an indication of the maximum level of investment that could be justified under different programs aimed at expanding CENAM's metrological services.

The objective of this exercise is to estimate how much society can invest in expanding the catalogue of metrological services of a National Metrology Institute (NMI) while maintaining social profitability. Specifically, the analysis seeks to identify the maximum justifiable level of investment, defined as the level at which the present value of the economic benefits generated by the expansion is at least equal to the associated investment costs.

This approach makes it possible to translate the economic benefits of metrology into a clear monetary metric, directly comparable to the infrastructure, equipment, and institutional strengthening costs required to expand service provision.

The analysis is based on the calculation of the Net Present Value (NPV) associated with the introduction of new "varieties" of metrological services, understood as new measurement capabilities materialized through additional calibration services offered by the NMI.

The exercise considers:

- A 20-year time horizon, consistent with the typical useful life of metrological equipment and the time required for associated economic benefits to fully materialize.
- A social discount rate of 12%, aligned with standard practices in economic evaluations of public projects in the region.
- Different initial levels of service varieties $(N_0)$ reflecting heterogeneity in starting conditions that may face other NMIs with different degrees of development.
- Alternative expansion scenarios**,** involving the incremental addition of 1 new variety, 25 new varieties, and 100 new varieties.

For each combination of initial number of varieties $(N_0)$ and the expansion level $(N_1 = N_0 + \Delta N)$, the NPV of the economic benefits generated by the increased availability and diversity of metrological services is computed. The results are presented in Table 7 below.

**Table 7. Net Present Value of Different Metrological Service Expansion Scenarios**

| $\boldsymbol{N_0}$ | $\boldsymbol{N_1 = N_0 + \Delta N}$ | | |
|---|---|---|---|
| | $\boldsymbol{N_0 + 1}$ | $\boldsymbol{N_0 + 25}$ | $\boldsymbol{N_0 + 100}$ |
| **100** | *25.5* | *414.2* | *720.8* |
| **587** | *4.4* | *101.6* | *321.2* |
| **1000** | *2.6* | *61.8* | *213.6* |

Source: Authors' elaboration.

The estimated NPV values can be interpreted as maximum investment thresholds. If the total cost of the expansion—including infrastructure, equipment, human capital, and operating costs—is less than or equal to the estimated NPV, the investment generates positive net economic benefits for society. If costs exceed this value, the expansion would no longer be socially profitable under the assumptions of the model. In this sense, the NPV does not represent expected expenditure, but rather the upper bound of economically justifiable investment from a social perspective.

Taking as an illustrative example an NMI such as CENAM, with an initial number of service varieties of $N_0 = 587$, the results indicate that adding a single new variety generates economic benefits whose present value can justify an investment of up to USD 4.4 million. A more ambitious expansion, involving the addition of 100 new varieties, could sustain a total investment of up to USD 321.2 million while maintaining a non-negative NPV.

These results highlight that the high marginal economic value of new metrological capabilities, even when starting from an NMI with an already extensive service catalogue, as is the case of

CENAM; and the presence of economies of scope and cumulative effects, whereby larger expansions generate substantial benefits at a systemic scale.

From a public policy and strategic planning perspective, these results are particularly useful because they provide a quantitative benchmark for assessing whether proposed investment amounts in metrology strengthening programs are economically reasonable.

Moreover, the results facilitate the prioritization of service catalogue expansions based on their contribution to aggregate welfare and reinforce the notion of metrology as an enabling economic infrastructure, whose social returns can substantially exceed costs—even under conservative assumptions.

Taken together, the estimated NPVs represent upper bounds of socially profitable investment and constitute a practical tool to guide financing and scaling decisions for National Metrology Institutes.

## Sensitivity Analysis

The economic benefits estimated in the baseline scenario depend on a set of structural parameters that are subject to uncertainty and may influence the social profitability of the expansion of metrological services. To assess the robustness of the results, a sensitivity analysis is conducted to examine how the Net Present Value (NPV) of different expansion plans varies in response to changes in key model parameters.

Table 8 reports the ranges used to sensitize two central parameters of the model: the elasticity of substitution between metrological service varieties and the output–profit elasticity. For both parameters, a triangular probability distribution is assumed. The parameter ranges are intentionally wide and therefore conservative. In the case of the elasticity of substitution, values are considered that extend beyond the estimation range reported in Table 2, with a greater deviation toward values that reduce the NPV. For the output–profit elasticity, the central value is set as the midpoint between the lower and upper bounds reported in the Mexico-specific literature, a conservative choice given that both values are below the corresponding estimates for the United States (De Loecker et al., 2019), which would imply higher NPVs.

**Table 8. Parameters Sensitized Using a Triangular Distribution**

| | Base parameter | Range |
|---|---|---|
| Elasticity of substitution between varieties | 1.31 | 1.2-1.7 |
| Output-profit elasticity | 0.26 | 0.15-0.37 |

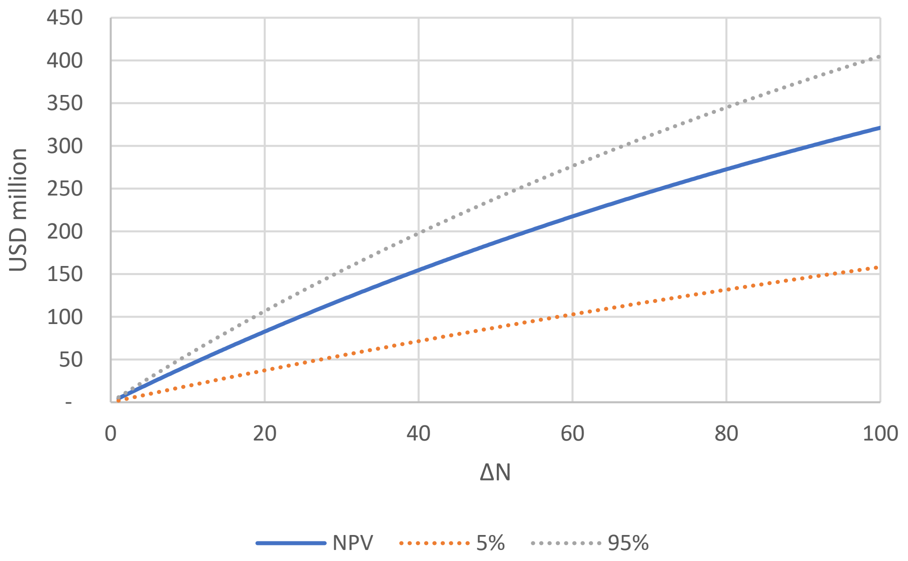
Source: Authors' elaboration.

Because the bounds of these ranges capture extreme and low-probability scenarios, the analysis relies on a Monte Carlo simulation approach. Probabilities are assigned to parameter values within the specified ranges, allowing for simultaneous variation in one or both parameters. This approach captures the joint probability of different parameter realizations and produces a distribution of NPV outcomes rather than a single point estimate. The simulations are based on 5,000 replications.

Starting from CENAM's initial catalogue of 587 metrological service varieties in 2024, Figure 5 presents the results of the sensitivity analysis for different expansion plans, expressed as a function of the increase in the number of service varieties (ΔN). The solid line shows the baseline

NPV estimates, while the dotted lines represent the 5th and 95th percentiles of the simulated NPV distribution.

**Figure 5. Net Present Value of CENAM's Different Metrological Services Expansion Plans**

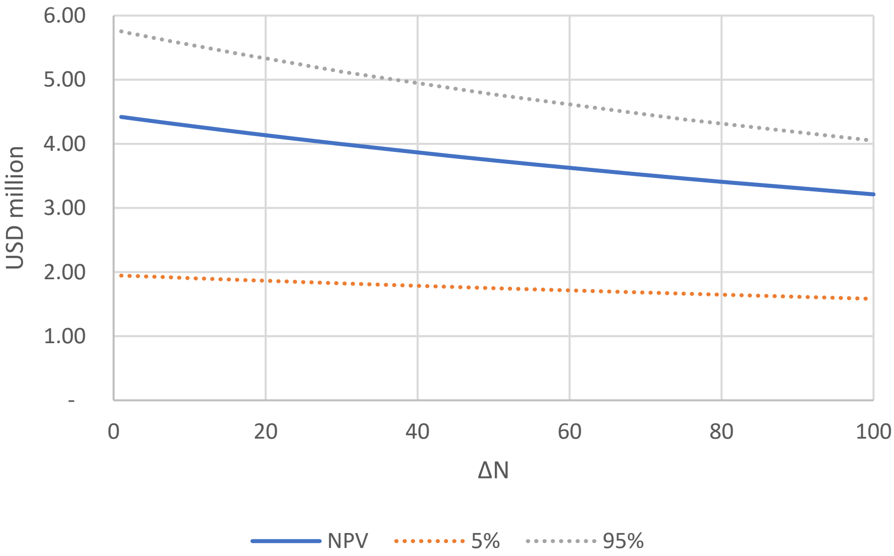



Source: Authors' elaboration

The results indicate that the estimated economic returns from expanding CENAM's metrological services are robust to substantial parameter uncertainty. The relatively narrow distance between the 5th and 95th percentile curves and the baseline NPV suggests limited downside risk. Even under conservative assumptions and adverse parameter combinations, the NPV remains positive for a wide range of expansion scenarios, reinforcing the conclusion that investments in expanding metrological service varieties generate positive net social benefits.

As a related result, Figure 6 reports the NPV per new metrological variety created under alternative expansion scenarios. The NPV per variety is obtained by dividing the total NPV of each expansion plan by the corresponding increase in the number of service varieties (ΔN). This normalization provides a measure of the economic value of the marginal variety at different expansion scales. The solid line shows the baseline estimate of NPV per variety, while the dotted lines represent the 5th and 95th percentiles derived from the sensitivity analysis.

**Figure 6. NPV per CENAM's New Metrological Variety Created**




Source: Authors' elaboration

Two main patterns emerge from the figure. First, the NPV per variety remains positive across all expansion scenarios, even under conservative assumptions, reinforcing the conclusion that expanding CENAM's metrological service catalogue generates positive net social benefits. Second, the NPV per variety declines as the size of the expansion increases, indicating diminishing marginal returns to the creation of additional varieties. While larger expansions generate higher total benefits, the incremental contribution of each additional service decreases as the catalogue becomes more extensive. From a policy perspective, this result is informative for sequencing and prioritization decisions. Smaller or targeted expansions tend to yield higher economic returns per variety, while larger-scale expansions remain socially profitable but require greater aggregate investment.

## IV. Conclusion

This paper set out to address a gap in the economic literature on metrology: the lack of robust, economy-wide estimates of its contribution to economic activity. While existing evidence documents high returns to metrology at the project, firm, or sectoral level, translating these findings into aggregate, policy-relevant metrics has remained challenging. By combining a microeconomic welfare framework with an input–output propagation mechanism, this paper provides an integrated approach to quantifying the economic impact of National Metrology Institutes.

Using Mexico's CENAM as a case study, the analysis shows that expanding the variety of metrological services generates sizable gains for secondary calibration and testing laboratories, which in turn propagate through production chains to affect a broad set of economic activities. Even under conservative assumptions, restoring CENAM's service catalogue to previous levels yields meaningful increases in laboratory activity and measurable gains in GDP. These results highlight the role of metrology as a systemic input that supports productivity across a wide range of sectors, including pharmaceuticals, automotive manufacturing, construction, energy, and mining.

Beyond point estimates, the paper introduces a net present value framework that allows the benefits of metrological expansion to be compared directly with investment costs. The resulting NPVs can be interpreted as upper bounds on socially justifiable investment, providing a concrete benchmark for public decision-making. The sensitivity analysis confirms that these conclusions are robust to substantial uncertainty in key parameters, with positive net benefits persisting even under adverse scenarios.

From a policy perspective, the findings reinforce the view of metrology as an enabling economic infrastructure with strong public-good characteristics and high social returns. Investments in expanding metrological capacity (through new service varieties, upgraded equipment, and institutional strengthening) are not merely technical expenditures, but strategic interventions that support competitiveness, innovation, and economic integration. The framework developed in this paper offers a practical tool for governments and development institutions to assess, prioritize, and scale such investments in a transparent and economically grounded manner.

The analysis is subject to several limitations that are worth acknowledging. First, by focusing on the variety dimension of metrological services, the framework abstracts from quality improvements, which may constitute an additional and quantitatively relevant channel through which NMIs generate economic value. The absence of quality data prevents this dimension from being incorporated into the current analysis, and future work with richer data could help quantify it. One potential avenue of analysis is the precision gain associated with metrological services expansion, something that has been considered in the case studies presented in Appendix 1. Second, the partial-equilibrium model builds on assumptions like constant output, and output effects through an output-markup elasticity which can be reconsidered. Third, the economy-wide propagation analysis relies exclusively on testing laboratories (NAICS 541380) as the channel through which metrological improvements reach the rest of the productive sector, excluding related activities such as repair and maintenance of electronic and precision equipment (NAICS 811219); the resulting estimates should therefore be interpreted as a lower bound on the aggregate impact. Finally, the framework does not capture the externalities associated with the public-good nature of metrology (including spillovers to innovation, consumer protection, and regulatory compliance) which fall outside the scope of the cost-benefit assessment but may substantially amplify the social returns estimated here.

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# Appendix 1: Case study for different new metrological services

## Restoration of capabilities in electromagnetic metrology

### Description of the project

Objective: Restore and expand CENAM's capabilities in electromagnetic metrology to measure electrical energy, support electromobility, and strengthen the electrical manufacturing sector.

Costs: USD 1,500,000 (Total acquisition cost) + USD 1,000 each year (Annual maintenance).

Technical impact: Reduced measurement uncertainty from: Electrical power and energy from 0.003% to 0.001%; High voltage and current from 0.01% to 0.001%.[20]

National energy context: 333.66 GWh of annual consumption, with an average generation cost of 99,500 USD/GWh.

Sectoral beneficiaries: *CFE* (Transmission, Distribution, Equipment and Materials Testing Laboratory, LAPEM), Automotive industry and electromobility, Manufacturers of transformers and meters, Calibration laboratories, and Electrical manufacturing sector.

### Economic impact estimation

We estimate the economic impact of the investment using a partial equilibrium model of the energy industry. To do so, we assume linear demand with a negative slope and, on the supply side, a Leontief production technology, which implies that the marginal cost function is constant and, therefore, supply is horizontal at the level of marginal cost.

We consider two alternative ways of measuring the economic impact of reduced measurement error: first, under the assumption that the investment reduces uncertainty in the measurement of electricity generation; and second, assuming that the reduced measurement uncertainty resulting from the investment lowers the industry's marginal cost of production.

Demand: $Q_d = a - bP$

Where $Q_d$ are the demanded quantities, $P$ is the price and $a$ , $b$ are the demand parameters.

Supply: $P = MC$

Where $MC$ is the constant marginal cost (linear cost function, Leontief production technology)

#### *Alternative 1*

Measurement error can be interpreted as a distortion in the amount measured and billed. If the error is high, some of the energy generated is not billed correctly or is lost in the system, which reduces the industry's actual revenue. Therefore, improving measurement reduces unaccounted-for technical losses (preventing billing errors), increases the amount actually sold at each price, optimizes the operation of power grids (especially for intermittent renewables), and prevents industrial damage caused by poor power quality.

Suppose the actual amount generated is $Q$. With a measurement error $e$, only $Q(1-e)$ is billed. Therefore, the actual revenue is: $R = P \cdot Q(1 - e)$ and the profit is $\Pi = (P - MC) \cdot Q(1 - e)$.

[20] Improved traceability and accuracy for wattmeters, power quality meters, and instrument transformers.

But if the measurement error is reduced, net revenue increases due to the recovery of technical losses. The improvement in measurement error from $e_1$ to $e_2$ generates an additional profit:

$$\Delta\Pi = (P - MC) \cdot Q(e_1 - e_2)$$

If we assume that some of the unbilled energy is recovered, then this benefit is positive and proportional to the improvement in metering. CENAM provided the following data:

- Peak demand: 55.6 GW
- Average generation cost: $99,500 per GWh
- Previous error: 0.01% = 0.0001
- New error: 0.0001% = 0.000001

$$Q = 55.6GW \times 24h \times 365 = 487{,}056GWh$$

$$P \times Q = 99{,}500USD \times 487{,}056 = USD\ 48{,}462{,}072{,}000$$

$$e_1 = 0.0001$$

$$e_2 = 0.000001$$

Based on those figures, assuming a 10% margin, we have that

$$\Delta\Pi = \frac{(P - MC)}{P} \cdot P \cdot Q(e_1 - e_2)$$

$$\Delta\Pi = USD\ 4{,}846{,}207{,}200(0.0001 - 0.000001) = \boldsymbol{USD\ 479{,}775}$$

That is the annual economic benefit resulting from the reduction in measurement error.

This would be a conservative estimate, given that the marginal cost of electricity generation in Mexico ranges from $40 to $60 per MWh for conventional technologies and is effectively zero for photovoltaic energy. In other words, the margin is likely to be well above 10%.

### *Alternative 2*

We assume that the marginal cost depends on measurement error. It is assumed that measurement error leads to additional costs due to oversizing of equipment, undetected technical losses, correction or redundancy costs, and operational inefficiency due to inaccurate information. We can model the marginal cost as:

$$MC(e) = MC_0 \cdot (1 + \alpha \cdot e)$$

Where $MC_0$ is the baseline marginal cost (without error), $e$ is the measurement error (proportionately, not in %), $\alpha$ is the parameter that captures the sensibility of costs to measure errors (how much the costs increases to a unitary change in errors).

Then, if $e > 0, MC(e) > MC_0$ reflects inefficiencies induced by uncertainty.

Suppose that the industry produces a fixed quantity $Q$ (for example, annual energy demand in MWh). The economic benefit of reducing the measurement error from $e_1$ to $e_2$ is the difference in marginal costs multiplied by the quantity produced:

$$\Delta\Pi = Q \cdot [MC(e_1) - MC(e_2)]$$

Therefore, the change in benefits equals:

$$\Delta\Pi = Q \cdot MC_0 \cdot \alpha \cdot (e_1 - e_2)$$

This expression shows that economic profit increases with the level of production, the base marginal cost, and the sensitivity of the marginal cost to measurement error, and decreases with improvements in measurement error.

Using CENAM data, a 10% margin (i.e., marginal cost equal to 90% of the price), and assuming $\alpha = 1$, meaning that a 0.01 (1%) increase in measurement error raises the marginal cost by 1%, the annual increase in project profits equals:

$$\Delta\Pi = 487{,}056 \cdot USD\ 99{,}500\ \cdot 0{,}9 \cdot 1 \cdot (0.0001 - 0.000001) = \boldsymbol{USD\ 4,317,971}$$

Currently, there is no direct, widely accepted empirical estimate of the parameter $\alpha$ that relates measurement error to the marginal cost of production in the electricity sector. However, there is indirect evidence and studies that support the model's logic:

1. Industrial energy efficiency studies: In industrial energy audits, it has been observed that measurement errors can lead to deviations of up to 2.4% between estimated and actual consumption[21]. This implies that operational decisions based on inaccurate data can result in cost overruns or inefficiencies.

2. Electricity markets and marginal costs: The marginal cost of electricity is highly sensitive to operational and dispatch conditions. In markets such as Chile's, increases of up to 76% in the daily marginal cost have been recorded due to changes in operating conditions and input prices[22]. This suggests that any factor affecting the accuracy of dispatch (such as measurement errors) can have significant effects.

3. Impact of measurement errors: Although they do not directly quantify $\alpha$, studies on measurement errors highlight that these errors can affect the planning, maintenance, and operation of power grids, resulting in additional costs.

### Impact of improvements in measurement on technical losses

According to CENAM, "The annual economic impact of technical losses in the productive sectors is indirectly estimated to reach up to 11 billion pesos (12.25% of the electricity bill in 2022, according to the CFE)." These technical losses amount to USD 611,111,111. Improved accuracy contributes to reducing undetected technical losses, optimizing the operation of power grids (especially with intermittent renewables), and preventing industrial damage caused by poor power quality.

If part of these losses is due to avoidable measurement errors, and the project helps reduce these losses by 1%, the annual economic benefit of the project is:

$$Economic\ benefits = 1\% \times USD\ 611{,}111{,}111 = \boldsymbol{USD\ 6,111,111}$$

## Outdoor laboratory equipped with instruments for measuring solar radiation

### Description of the project

Objective: Offering a remote pyranometer calibration service.

Costs: USD 402,537 (Total acquisition cost).

[21] Portillo Ramos et al. (2020), available at 1909-0455-pml-15-01-49.pdf

[22] Hallack et al. (2022), available at ¿Qué sucede con los costos marginales de la electricidad en la región? - Energía para el Futuro

Technical impact: According to information provided by CENAM, without pyranometers, photovoltaic plants measure solar radiation based on satellite data, which has a margin of error of 15%. With indoor pyranometers in a simulated environment, the margin of error is 1.8%; with outdoor pyranometers, it is 2%. The difference is due to calibration being performed in a controlled environment versus outdoors. Internal calibration takes 3 weeks. During that period, the customer must rely on satellite data. With this operation, equipment will be acquired to perform external calibrations, which, although it has a 0.02% higher error, saves the 3 weeks of increased inaccuracy that occur with internal calibration. Therefore, the effective measurement error without the project is equal to (0.018 × (365 – 21) + 0.15 × 21) / 365 = 0.0256, while the effective measurement error with the project is (0.02 × (365 – 4) + 0.15 × 4) / 365 = 0.0214, given that external calibration can take between 3 and 5 days depending on external conditions. Therefore, the reduction in measurement uncertainty varies from 2.56% (in-house calibration) to 2.14% (remote calibration).

National energy context[23]: 20,000 GWh of annual consumption, with an average generation cost of 40,000 USD/GWh.

Sectoral beneficiaries: Photovoltaic energy (plants, controllers, manufacturers).

## Economic impact estimation

We estimate the economic impact of the project using a partial equilibrium model of the photovoltaic industry, under the same assumptions as in the previous case.

### *Alternative 1*

As shown in Case 1, the improvement in measurement error from $e_1$ to $e_2$ helps improve production measurement and generates an additional benefit of:

$$\Delta\Pi = (P - MC) \cdot Q(e_1 - e_2)$$

Based on the following data:

Peak demand: 20 GW with an average generation cost of USD 40,000 per GWh

Previous error: 2.56% = 0.0256

New error: 2.14% = 0.0214

$$P \times Q = 40{,}000USD \times 20{,}000 = USD\ 800{,}000{,}000$$

$$e_1 = 0.0256$$

$$e_2 = 0.0214$$

With this data, assuming a 10% margin, we have that

$$\Delta\Pi = \frac{(P - MC)}{P} \cdot P \cdot Q(e_1 - e_2)$$

$$\Delta\Pi = USD\ 80{,}000{,}000 \cdot (0.0256 - 0.0214) = \boldsymbol{USD\ 336{,}000}$$

That is the annual economic benefit resulting from the reduction in measurement error.

[23] https://imco.org.mx/monitor/energia/

This would be a conservative estimate, given that the marginal cost of photovoltaic power generation is very low and close to zero.

*Alternative 2*

As shown in Case 1, the change in profit due to the lower marginal cost associated with the smaller measurement error is:

$$\Delta\Pi = Q \cdot [MC(e_1) - MC(e_2)] = Q \cdot MC_0 \cdot \alpha \cdot (e_1 - e_2)$$

That is, using the data from Alternative 1, the project generates an increase in annual economic benefit of:

$$\Delta\Pi = 800{,}000{,}000 \cdot 0.9 \cdot 1 \cdot (0.0256 - 0.0214) = \boldsymbol{USD\ 3{,}024{,}000}$$

# Appendix 2. From Variety Expansion in Calibration Services to Economy-Wide Impacts

This appendix presents the analytical framework used to quantify the economy-wide impact of an expansion in the supply of calibration services. The approach uses a supply-driven input–output (IO) Ghosh model (Ghosh, 1958) that captures the propagation of sectoral shocks through production linkages.[24]

The Ghosh (supply-driven) model captures how an exogenous increase in activity in a given sector propagates through the production network via forward linkages. In this framework, a positive supply shock in sector $k$ (e.g., calibration services) expands its output and, given fixed allocation coefficients, increases the supply of intermediate inputs to all downstream sectors in proportion to the shares of sector $k$ 's sales across those sectors (i.e., along the rows of the input--output matrix). These downstream sectors, in turn, expand their own production, generating further rounds of indirect effects throughout the economy. Implicitly, this mechanism assumes (i) perfect pass-through of additional supply to downstream users, (ii) fixed output allocation shares (no substitution across destinations), and (iii) the absence of demand constraints, such that all additional output is fully absorbed. Under these assumptions, the model provides a tractable representation of how sectoral supply expansions translate into economy-wide increases in activity.

## Input–Output Propagation (Ghosh Model)

Denoting by $x_j$ total output of sector $j$, $z_{ij}$ the sales from sector $i$ to sector $j$, and $v_j$ the value added of sector $j$,

$$x_j = \sum_i z_{ij} + v_j$$

Define allocation (row) coefficients as

$$b_{ij} = \frac{z_{ij}}{x_i}$$

Where $b_{ij}$ is the share of sector $i$ 's total output that is sold to sector $j$,so that

$$x_j = \sum_i b_{ij} x_i + v_j.$$

which in matrix form becomes

$$\boldsymbol{x} = \boldsymbol{x}\boldsymbol{B} + \boldsymbol{v}.$$

The supply-side equilibrium condition states that total output equals the sum of value-added propagated forward through all rounds of inter-industry supply.[25]

Therefore,

$$\boldsymbol{x} = \boldsymbol{v}(\boldsymbol{I} - \boldsymbol{B})^{-1} \equiv \boldsymbol{v}\boldsymbol{G}$$

[24] The Ghosh model has been widely used in input-output frameworks (Altimiras-Martin, 2024; Dietzenbacher, 1997).

[25] Note that $\boldsymbol{B} = \boldsymbol{x}^{-1}\boldsymbol{Z}$ where each row of $\boldsymbol{B}$ sums to a value less than or equal to 1; the remainder represents value added. This is the supply-side analogue of Leontief's technical coefficients, but normalized by row (seller) rather than by column (buyer).

Where $\boldsymbol{G} = (\boldsymbol{I} - \boldsymbol{B})^{-1}$ is known as the Ghosh inverse matrix. Each element $g_{ij}$of $\boldsymbol{G}$ measures the total output of sector $j$ generated per additional unit of primary input (value added) supplied by sector $i$. The row sums of $\boldsymbol{G}$ are the output multipliers: a larger row sum for sector $i$ means a supply expansion there generates more economy-wide output.

A supply shock in calibration services is modeled as:

$$\boldsymbol{v}' = \boldsymbol{v} + \Delta\boldsymbol{v}, \quad \Delta\boldsymbol{v} = (0, \dots, \Delta v_k, \dots, 0)$$

The resulting change in output is:

$$\Delta\boldsymbol{x} = \Delta\boldsymbol{v}\boldsymbol{G} = \Delta v_k \cdot \boldsymbol{G}_{k\cdot}$$

In this expression $\boldsymbol{G}_{k\cdot}$ is the row $k$ of the Gosh inverse. That is, the induced output change across all sectors is obtained by pre-multiplying the shock vector (as a row vector) by the Ghosh inverse. Because $\boldsymbol{G}$ captures all rounds of indirect supply linkages, $\Delta\boldsymbol{x}$ includes both the direct output increase in sector $k$ and all downstream effects on sectors that purchase from $k$.

## Mapping to Aggregate GDP

GDP in the input-output framework equals total value added. Define the value-added coefficients as:

$$\alpha_j = \frac{v_j}{x_j}$$

Then aggregate GDP changes according to:

$$\Delta GDP = \boldsymbol{\alpha} \cdot \Delta\boldsymbol{x} = \Delta v_k \cdot (\boldsymbol{\alpha} \cdot \boldsymbol{G}_{k\cdot}) = \Delta v_k \times m_k$$

where $m_k$ is the output multiplier given by $m_k = \sum_j \alpha_j g_{kj}$.

## Integrated Interpretation and critical assumptions

The full mechanism can be summarized as follows:

1. The increase in CENAM's varieties is mapped into an increase in real value added in the calibration services sector ($\Delta v_k$).
2. The increase in supply propagates through forward linkages captured by the Ghosh inverse ($\boldsymbol{G}$).
3. Downstream sectors expand output, generating additional value added across the economy.
4. The total GDP impact is given by $\Delta GDP = \Delta v_k \times m_k$.

This integrated framework combines two layers of assumptions:

- **IO propagation:** Output allocation shares are fixed, and supply shocks are transmitted proportionally through production linkages.
- **No price adjustment:** The model operates in real quantities, abstracting from equilibrium price responses.

- **Full absorption:** Increased supply of calibration services is fully utilized by downstream sectors.

While the validity of these assumptions may be open to question, the framework provides an analytically tractable basis to connect improvements in metrology capacity with macroeconomic outcomes.