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Evaluation of the Economic Impact of Electricity Blackout Scenarios for the Automotive Sector and the Slovak Economy¹

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Abstract

We estimate the economic consequences of electricity blackout scenarios on the automotive industry and the Slovak economy. Our estimates of inoperability of the automotive sector range from 2.9 % to 4.2 % across regions on the first day of the blackout, while the overall inoperability of the economy during a three-day blackout would reach up to 10 %. The economy would suffer a loss of final demand ranging from €34.28 million in the most optimistic scenario to €122.49 million in the least optimistic scenario. We note a relative resilience of the automotive sector compared with the vulnerability of the economy. We document substantial regional heterogeneity in the distribution of economic impacts. The model has wide potential for further use by public policy makers as well as stakeholders in economic resilience planning. The main value added of this paper is the high regional resolution of the model at NUTS 3 level, which allows accurate quantification of losses in individual regions, as well as original and flexible framework for temporal modelling of economic impacts based on hourly/daily electricity consumption indices and monthly industrial production indices.

Keywords: Inoperability Input-Output model, automotive industry, electricity, blackout, electric grid, economic impacts, critical infrastructure, scenario modelling

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Introduction

The modern world depends on electricity. Power outages pose a serious threat to modern highly specialised and technology intensive industries, such as the automotive industry. In 28th of April 2025, Spain was hit with a massive blackout, causing an immediate loss of 60% of the electrical load. The lives of millions of people on the Iberian Peninsula were impacted, while disrupting factories, hospitals, transport systems, mobile networks and other critical infrastructure [1].

Recent events directly affecting the energy sector go beyond sporadic examples. The war in Ukraine, unprecedented threat of cyberattacks, and the potential instability of electricity grid, increasingly highlight the need for reliable methods for estimation of regional, economic blackout-induced losses. Given the high energy intensity of production processes in Slovakia [2], even a short-term power outage can cause serious economic losses, disrupt supply chains, and threaten the competitiveness of businesses. Meanwhile, intensive and ongoing development of new green sources of energy [3], in combination with worsening security situation and the unprecedented threat of cyberattacks [4], are placing increasing demands on the electric grid, which has been suffering from an investment deficit for many years [5].

Relative security in previous decades has led to an underestimation of the role of predictions of regional disaster impacts in public policy, not only in the technical but also in the economic field in Slovakia [6]. In the effort to deploy adequate policy measures to strengthen the resilience of economy, we evaluate the economic impacts of possible blackout scenarios and their induced loss of output of most significant sectors.

The objective of this paper is to evaluate the economic losses and relative inoperability caused by a hypothetical nationwide electricity blackout in Slovakia, focusing on the car industry and its propagation at the national level as well as across NUTS 3 regions. The paper aims to quantify economic disruptions across regions, taking into account variations in production capacities, supply chain dependencies, and intersectoral transactions. A scenario-based approach is developed to capture the uneven responses of different sectors to power disturbances over the duration of the blackout, as well as variations in responses depending on the state of the electricity grid. Scenario modelling is performed with differing recovery trajectories (slow, moderate, rapid) and variant blackout timings (summer/winter, morning/afternoon), based on official grid recovery policies and possible blackout whereabouts.

The paper is structured as follows. Section 1 provides an overview of the operation of transmission system in the Slovak Republic and a literature review on modelling inoperability and its

economic impacts. Methodology, data and scenarios are presented in Section 2. First, Inoperability Input-Output model is elaborated, followed by the explanation of regionalisation of national input-output tables. Lastly, scenarios based on different blackout duration, season and day-time occurrence are explained. Own scenario-based approach is developed to capture different grid states. Section 3 presents the main empirical results.

1 Transmission System, Inoperability and Economic Impacts

We first review the peculiarities of electricity generation and transmission systems in general as well as in the case of Slovakia. Then we review the literature on modelling the economic impacts of inoperability due to electricity blackouts.

1.1 Electricity Generation and Transmission System of Slovakia

From an economic point of view, electricity is a very specific commodity. Unlike different utilities, electricity cannot be created, stored, and used later. The supply must match demand at every moment. This property makes it susceptible to even small disturbances and therefore requires complex methods of managing properties of the grid. A blackout is a situation where a total power outage occurs for more than three minutes in the entire system of the Slovak Republic, or a significant part of it [7]. The factor triggering this process is usually an imbalance between electricity production and its consumption at a given moment. This can be caused, for example, by a sudden failure of a major power generation source, or by a series of faulty line shutdowns that cause the system to be disconnected. However, it is likely, that nationwide blackout in Slovakia would require the interplay of several technical, natural and organizational factors. Examples of these can be excessive load on lines, insufficient backup and inertia of growing green energy sources alongside nuclear plant power outage, shutdown of key transformers or a possible cyber-attack on the dispatching centre. However, the cause may not be endogenous at all. Increasing the share of renewables in the total energy mix in the countries of the interconnected ENTSO-E network puts increasing demands on the transmission systems of individual countries and increases the vulnerability of the whole. The fact that Slovak transmission system is part of an interconnected European system is associated with the advantage of easier frequency management, but at the same time increases the risk of propagation of disturbances originated outside of Slovakia [7]. Restoring electricity supply following a large-scale outage presents a complex technical challenge, primarily due to the need to restart generation facilities. Under normal conditions, power plants rely on the broader grid to assist in resuming operations. However, when the grid is entirely de-energized, a procedure known as a black start must be implemented to initiate power

generation independently. Typically, transmission operators begin by establishing isolated “power islands” – a self-sufficient segment of the grid that are later synchronized and integrated. Consequently, different regions may experience staggered and differing recovery paths [8], [9].

1.2 Modelling Inoperability and Economic Impacts

Modelling the economic impacts of a disaster can be approached using a variety of methods [10]. In this paper, we focus on input-output (I-O) analysis methods that allow us to capture direct and indirect effects of exogenous shocks that propagate through interindustry linkages. Given the short-term and sector-specific nature of blackout impacts, I-O models are well-suited to capture interindustry dependencies and the cascading consequences of disrupted production. Unlike CGE or econometric models, I-O analysis does not rely on complex behavioural assumptions or extensive historical data, which are limited for rare events, like large-scale blackouts. Additionally, the ability to integrate I-O models with engineering or energy system data enhances their relevance in this context. Despite some limitations, such as fixed technical coefficients, the I-O framework offers a pragmatic and robust approach for this type of shock analysis.

Input-output analysis has been widely applied in economic impact assessments, particularly in estimating the consequences of power outages [11]. According to [12], the traditional use of the I-O model for analysis of major economic changes has already been expanded to a wide array of applications, including disaster risk management, environmental impact analysis, and energy consumption among others. An important contribution by Anderson and Geckil [13] evaluated the 2003 Northeast Blackout in USA, using I-O multipliers, estimating a total loss exceeding \$6 billion. They emphasized the limitations of standard I-O analysis in capturing temporal dynamics, suggesting the incorporation of time-sensitive variables. Henriot et al. [14] combined I-O frameworks with network theory to assess cascading failures, showing that sectoral interdependencies significantly amplify economic shocks, particularly in critical infrastructure sectors. Lian and Halmes [15] developed the Inoperability Input-Output Model (IIOM), by introducing the concept of “inoperability” measured as normalised production loss for analysed sectors. This concept builds on previous concepts of supply-side model introduced in 1958 by Ghosh [16] and its reinterpretation by Dietzenbacher in [17]. Another notable use of this approach measures financial and inoperability effects to post-estimate effects of the 2003 Northeast USA Blackout [18] as well as series of similar catastrophe modelling studies – the study is notable by introducing dimension of economic losses caused by unavailability of workforce during blackout event. Galbusera and Giannopoulos [19] explored I-O models in disaster risk assessment, emphasizing their role in differentiating between direct losses and cascading

economic effects. They concluded that while traditional I-O models are useful for short-term assessments, hybrid behavioural enhanced models offer greater accuracy for multi-regional loss quantification and resilience assessment. In 2005, Andersson et al. suggested integrating risk-based system security assessment to mitigate impacts of wide-area blackouts. They analysed the causes and consequences of the 2003 major blackouts in North America and Europe, emphasizing that system-wide cascading failures and inadequate situational awareness were key contributors to incurred losses [20]. Guilhoto et al. in [21] proposed integrating geographic information systems with I-O models to disaggregate and enhance spatial precision in economic impact assessments. This aligns with Koks et al. [22] that emphasized that economic losses from blackouts vary based on geographic and socio-economic factors. Therefore, combination of regionalisation techniques and I-O models can provide a more granular understanding of localized economic disruptions. Despite methodological advancements, discrepancies remain in loss estimations across studies due to varying assumptions about substitution effects, resilience measures, and sectoral interdependencies. While traditional I-O models provide rapid assessments, hybrid approaches integrating CGE, consumer damage function and network-based models offer improved accuracy in capturing long-term economy adaptation dynamics.

2 Methodology, Data and Scenarios

2.1 Inoperability Input-Output Model

The Inoperability Input-Output Model extends the traditional Input-Output analysis by introducing the concept of inoperability, which quantifies the extent to which sector performance is affected by exogenous disruptions. According to [12], this allows for a more nuanced understanding of cascading failures in interconnected systems, providing a robust framework for evaluating economic and infrastructure resilience. Given the foundation of basic Leontief Input-Output model, the IIM is suitable for evaluating both immediate and cascading impacts caused by a regional blackout, as well as to determine the cascading impacts across interdependent sectors within the region of interest [12], [23], [24].

The IIM builds upon traditional I-O analysis by introducing the concept of inoperability, represented by “normalized production loss”, firstly introduced by Haimes and Jiang in [23], defined as:

$$\text{Normalized production loss} = \frac{\text{As planned production} - \text{Degraded production}}{\text{Nominal production}}$$

Normalized production loss represents the level of a system's dysfunction, expressed as a percentage of its 'as-planned' production capacity. In context of this paper, inoperability will be a synonym to this normalised production loss. Inoperability takes on values between 0 and 1, where 0 corresponds to the 'as planned' performance level and 1 corresponds to a completely inoperable system [12]. Economic loss is the second, different metric, generated from IIM analysis, representing the monetary loss associated with an inoperability value.

For \mathbf{x} representing the vector of a planned production and $\tilde{\mathbf{x}}$ the vector of degraded production, we can define inoperability vector \mathbf{q} with individual elements q_i as follows

$$q_i = \frac{x_i - \tilde{x}_i}{x_i}.$$

Standard I-O model can thus be adjusted for the degree of inoperability of individual sectors

$$\mathbf{q} = \mathbf{A}^* \mathbf{q} + \mathbf{y}^*,$$

where \mathbf{y}^* is a perturbation vector expressed in terms of normalized degraded final demand. Therefore, a supply-based reduction is treated as a forced demand reduction. We model this element as product of rate of power outage to nominal electricity supply and nominal final demand ratio. \mathbf{A}^* represents the interdependency matrix (inoperability augmented version of input coefficient matrix \mathbf{A}), conceptually representing the first level interdependency between the respective industries in the context of inoperability. The elements in a particular row of this matrix can tell how much additional inoperability is contributed by a column industry to the row industry.

Similarly to linkages in basic Leontief I-O model, IIM offers general metrics to compare the vulnerability of one's own sector to external influences, as well as the impact of one's own sector on the vulnerability of other sectors. For this purpose, "dependency index" (σ_i) and "influence gain" (ρ_j) are usually utilised [23], [25]

$$\sigma_i^{overall} = \frac{1}{n-1} \sum_{j \neq i}^n a_{ij}^* \quad \rho_j^{overall} = \frac{1}{n-1} \sum_{i \neq j}^n a_{ij}^*,$$

in which a_{ij}^* represent individual elements in matrix \mathbf{A}^* .

The final IIM model describes the impact of sector perturbations both on inoperability of each sector, as well as monetary represented economic loss. Besides sole effects of electricity shortage, workforce unavailability represent major factor contributing to blackout outcome. By applying IIM perturbation to the energy sector, it is possible to capture the direct and induced effects of energy scarcity, primarily from the point of view of production technologies – in the context of economic theory, it is the capital side of the production function. However, a disaster of this type will also cause

extensive impacts on the ability and workers to get to their work and then conduct their activities in the creation of the overall product. At the same time, such perturbations in the workforce can spread very intensively through ripple effects to other parts of the economy, in an analogous way to a primary power outage. Modelling perturbation exclusively in electricity sector would, by the nature of I-O analysis oriented towards technological relations represented by A , cause ignoring the dimension of labour induced impacts. For this reason, in our model, we differentiate between two sources of perturbation impacts – impacts caused by primary energy shortages in the production process and impacts on workforce with their subsequent consequences. We define the sensitivity of individual sectors to the unavailability of the workforce through the share of compensations of employees in the total product of the given sector. Perturbation vector $\mathbf{y}^*_{\text{labour}}$ is then expressed as a product of this ratio and the blackout intensity rate, corresponding to the modelled day of its duration.

Inoperability vector $\mathbf{q}_{\text{electric}}$ represents inoperability caused by electric grid perturbation and inoperability vector $\mathbf{q}_{\text{labour}}$ represents inoperability induced by workforce unavailability. Both are functions of normalized technical coefficients matrix \mathbf{A}^* , and their respective perturbation vectors $\mathbf{y}^*_{\text{electric}}$ and $\mathbf{y}^*_{\text{labour}}$, whose elements stand for respective inoperability of each sector i . To quantify economic losses, inoperability is multiplied by final demand vector and other elements of the I-O table. The result of the calculation are economic losses related to the length of the period captured in the I-O table (1 year). Finally, economic losses are recalculated for specific inoperability duration in days based on specific scenarios.

2.2 Regionalisation of Input-Output Tables

To account for regional heterogeneity of blackout impacts we constructed regional I-O tables for the Slovak economy as these tables are not provided by any other publicly available data source. Regional I-O tables for individual NUTS 3 regions, which are based on the I-O table at the level of the whole Slovakia. The variable that we use to define the "presence" of sectors (broken down into NACE Rev. 2, division level - two digit) in individual regions is the average registered number of employees (as individuals) in individual sectors, provided by the Statistical Office of the Slovak republic. Regional tables are obtained by adjusting the exogenous quantities of final demand \mathbf{Y} and the matrix of technological coefficients \mathbf{A} in individual regions of the Slovak Republic and converting the global multi-region Input-Output table into a single region. Despite the fact that single-region models cannot be used to estimate interregional feedback effects [26], the loss of accuracy is not significant for small regions, as they are in Slovakia.

For derivation of regional technical coefficients matrices A_{reg} , we use concept of cross-industry location quotients (CILQ). CILQ compares the ratio of the selling industry's employment of the region to the purchasing industry in the region to the same ratio on the national level. The suitability of this approach is given by the fact, that in addition to the degree of the presence of a given sector in the region, it can also approximate the degree of occurrence of mutual transactions between individual sectors. Within this approach, we use the assumption that there are no differences between production technologies across regions in each sector. In practice, for example, for the automotive sector, this means that the sum of materials needed to produce a car does not differ significantly depending on whether it is produced in the Bratislava or Košice region. We consider this assumption to be highly probable given the structure of the Slovak economy. The disadvantage of the CILQ is that it does not account for regional size and transport distances, [27] however due to regional specifics of Slovakia, such as the relatively similar size of the regions, this does not present a significant problem for the purposes of this analysis.

2.3 Data

Our main data come from *Environmentally Extended Input-Output Database (Exiobase)* [28]. It is a global multi-regional input-output database that integrates economic and environmental data at a very detailed level and enables the analysis of the environmental impacts of consumption and production within global supply chains. For the purpose of this paper, we worked with global I-O tables in version B, in the industry x industry format [26] for the period 2013 to 2022, which at the time of writing the paper represented the most recent available year. Original data (163 sectors) were aggregated to 59 sectors that are compatible with the European nomenclature NACE Rev. 2 [29]. The aggregation was based on publicly available concordance tables (Exiobase – NACE Rev. 2) [30] and sectoral availability of data on employment provided by the Statistical Office of the Slovak Republic.

To create electricity consumption indices for the purpose of modelling time-differentiated economic losses, we use data on the load on the electricity system of the Slovak Republic, provided by the Slovak Electricity and Transmission System, a. s. (SEPS a. s.). These are data on the load of the system expressed in MW with a resolution of 1 hour within individual days of the year in the range of 1st of January 2022 to 31st of December 2022.

To improve the estimation of the impact on industrial sectors, which differ temporally in the nature of production, we use data from the industrial production index in individual months of 2022, provided by the Statistical Office of the Slovak Republic. Data on employment within individual Nace Rev. 2 sectors of the economy at the NUTS 3 regional level also come from the same source.

2.4 Scenarios: Blackout Duration, Season, and Day-time Occurrence

Economic losses described in the methodology represent “yearly average losses”. However, this reasoning is not valid, as the given duration of the blackout (stemming solely from the electricity production sector, not accounting for unpredictable large-scale exogenous factors) is extremely unlikely for the Slovak electricity system. Validity of this approach would be furtherly compromised by possibility of a certain, gradual adjustment of technical coefficients and prices in the economy to new conditions arising because of the shock, which cannot be reliably modelled through the utilized framework. In addition, due to the changing demand for electricity over the span of year, the economic losses caused by the blackout will not be evenly distributed. Electricity is not consumed uniformly over time. Electricity consumption shows specific patterns throughout the year (Figure 1) and throughout the day (Figure 2), reflecting a combination of climate, economic, and social factors.

Figure 1 Average loads on Slovak electric grid in days of year, 2022 – data for seasonal index

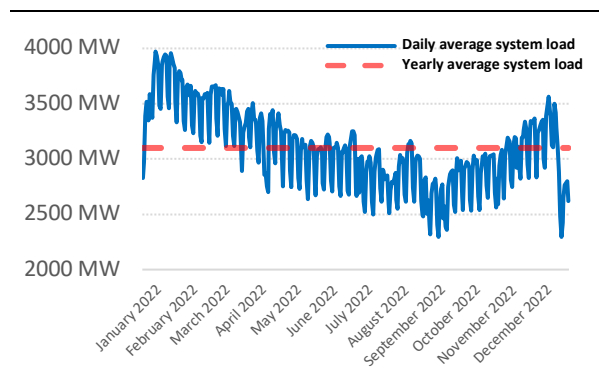
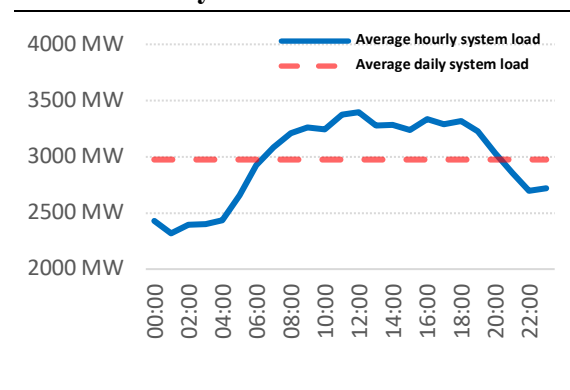


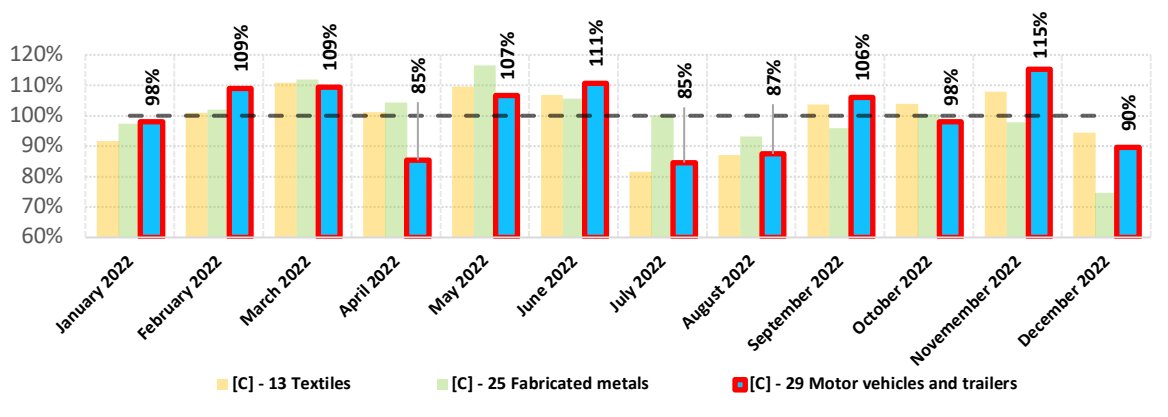
Figure 2 Average loads on Slovak electric grid in hours of day, 2022 – data for daily index



Source: SEPS a. s., authors' elaboration.

To implement this variation, we normalize yearly losses to 1-day resolution losses, as well as introduce sector-specific daily and seasonal electric system load indices. We do apply these indices to primary and tertiary sectors, as these are the sectors in which the electricity consumption is mainly centred around daily and seasonal variations. For example, field works are dependent of the daylight, and employees in administrative buildings require more intense heating during winter. As result, electric consumption closely resembles that of the whole country.

Figure 3 Monthly index of industrial production in automotive and selected sectors, 2022



Source: ŠÚ SR.

On the other hand, production in industrial sectors often does not follow the cycles defined above. Most major producers operate in shift mode, with the distribution of electricity consumption (which here depends to a significant extent on production) over the year being influenced more by orders and business-contracting factors (Figure 3). As a result, consumption patterns of the economy as a whole are not fully resembled. At the same time, there may be a significant discrepancy between the consumption peaks of individual sectors. Therefore, in addition to overall electricity load data, we use data on the volume of industrial production in individual months of 2022, provided by the Statistical Office of the Slovak Republic. Overall electricity consumption data are then weighted, based on their correlation coefficient with production index data. This ensures that the more the annual production pattern resembles the national electricity load, the more the relevant industry index follows the value of the national seasonal index. This process results in compilation of special index expressing the ratio of the production of the individual industrial sector in a certain month to its average monthly production, while also accounting for the national electricity load pattern.

Technical conditions for access and connection, rules for the operation of the transmission system, SEPS a. s. [9] documents technical aspects of defence and restoration of the electricity network in cases of disruption in stability of the electricity supply at the level of the transmission system, and blackout recovery process. Based on this document, we adopt three scenarios of electricity load recovery path. Moderate reduction of electric sector perturbation through blackout duration (Scenario A), rapid reduction of perturbation through duration (Scenario B) and slow reduction of perturbation through blackout duration (Scenario C). Within our framework, these scenarios are implemented through different perturbation vectors \mathbf{y}^* for each day of analysis. We have chosen three-day duration as the most probable, given previous blackouts in Europe and the world (see for example [12], [20]).

Table 1 Blackout recovery rate scenarios

	Blackout intensity (as % of unfulfilled electricity demand)		
	1 st Day	2 nd Day	3 rd Day
Scenario A – Moderate rate of recovery	99%	50%	10%
<i>Specifics for a Bratislava region</i>	99%	25%	5%
Scenario B – Rapid rate of recovery	99%	25%	5%
<i>Specifics for a Bratislava region</i>	99%	12,5%	2,5%
Scenario C – Slow rate of recovery	99%	75%	20%
<i>Specifics for a Bratislava region</i>	99%	37,5%	10%

Source: Authors' elaboration.

In the table above, we summarize blackout intensity, defined as % of unfulfilled electricity demand in respective days of each scenario. Please note variable perturbation for region of Bratislava. This is due to preposition in aforementioned document, stating priority in electric service restoration for the region of capital city. We model this by implementing half-intense perturbation (compared to other regions of country) in the days after the first day of blackout occurrence. In the first day, intensity is equal for all regions and scenarios, given that blackout firstly brings total outage to all sectors without distinction. For initial perturbation, we have chosen level of 99 %, to account for presence of stand-alone renewable electricity sources operationally independent of the grid.

Table 2 Proposed scenarios of blackout occurrence within year

SCENARIO – second instance	Date of blackout occurrence / duration	Daily average system load	% of yearly average el. system load	% of yearly average industrial production in automotive
Scenario A, B, C autumn (Saturday)	10 th of September 2022	2406,8 MW	77,6%	132,6%
	11 th of September 2022	2295,5 MW	74,1%	
	12 th of September 2022	2639,8 MW	85,2%	
Scenario A, B, C winter (Tuesday)	18 th of January 2022	3881,9 MW	125,2%	122,7%
	19 th of January 2022	3924,6 MW	126,6%	
	20 th of January 2022	3945,9 MW	127,2%	

Source: data - SEPS, a.s, scenarios - own proposal

Additionally, we consider seasonal aspects of blackout occurrence. We have chosen two arbitrary dates – 10th of September, and 18th of January – as both of them represent different electricity consumption states by means of total load placed on grid, and thus provide good comparison vantage points. The differences are driven mainly by overall seasonal consumption patter (which is higher during winter), as well as working days (where consumption is higher during weekdays).

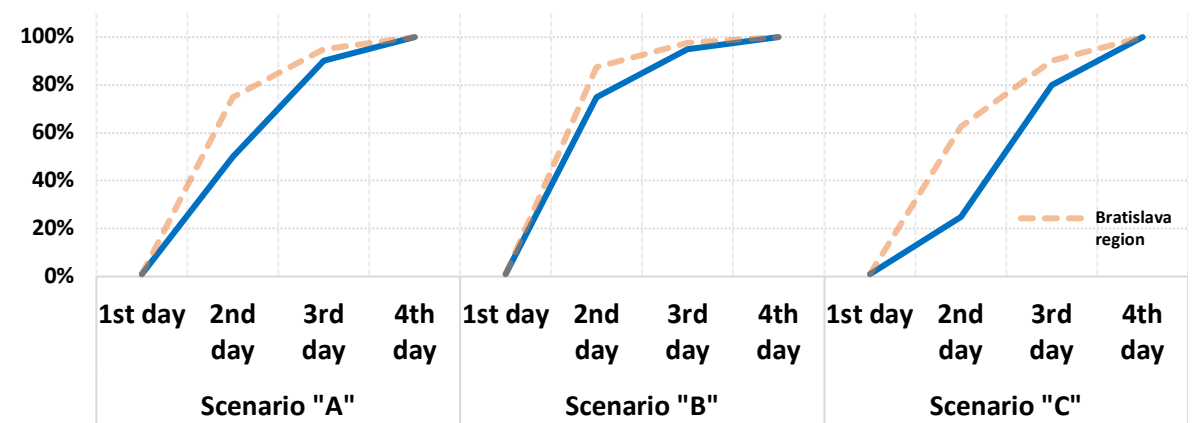
Table 3 Proposed scenarios of blackout occurrence within day

<i>SCENARIO – third instance</i>	Daytime of blackout occurrence	<i>Hourly system load</i>	<i>% of daily average system load</i>
<i>Scenario A, B, C – morning</i>	00:00	2426,1 MW	81,6%
<i>Scenario A, B, C – afternoon</i>	13:00	3278,1 MW	110%

Source: SEPS, a. s., scenarios authors' elaboration.

Finally, we model blackout occurrence within a day. This approach accounts for a fact, that occurrence within different time of a day has different implications for total losses. For example, one can expect bigger immediate losses if a blackout occurs at 13:00 during business day than at midnight during weekend. On the other side, full day losses will be probably higher, due to matter of fact there are still several hours left in the day during which the condition can cause losses.

Figure 4 Blackout recovery paths modelled within implemented scenarios



Source: Author' elaboration.

Our research framework allows for certain degrees of freedom for future analyses. Analysts can arbitrarily model various blackout circumstances: blackout duration, day of occurrence, daytime of occurrence and recovery path. Every dimension can also vary between regions, as well as between individual sectors. However, it should be kept in mind that accuracy of impacts evaluation can only be reliably maintained for a short time span of blackouts as it assumes fixed prices, fixed inputs to production, etc.

3 Empirical results

This chapter presents the empirical outcomes of the blackout impact modelling on the economy, based on regionalized Inoperability Input-Output framework. Graphical outputs support the quantitative assessment, reflecting sectoral exposure, and temporal vulnerability across multiple

blackout scenarios. All figures and estimates refer to the 2022 base year of the analysis in the year is not explicitly stated.

3.1 Inoperability of Automotive Sector by Different Blackout Scenarios

In this subchapter, we present inoperability of automotive sector by different scenarios. The automotive industry forms the basic pillar of the Slovak economy with a share of 10.4% of GDP and 46.5% of total sales from industrial production. Around 255 000 people work directly and indirectly in the sector, equivalent to around 5% of the country’s total population. Annual car production reaches approximately 1.08 million units (2023), which ranks Slovakia among the 20 largest car manufacturers in the world. With 199 cars produced per 1,000 inhabitants, Slovakia is the world leader in the production of vehicles per capita [31]. Currently, there are four established manufacturers operating in Slovakia: Volkswagen (Bratislava), Kia (Žilina), Stellantis (Trnava), Jaguar Land Rover (Nitra). In addition, the construction of a new Volvo plant near Košice is planned, which should employ about 5 000 people, with another 12 000 positions in supplier companies. The carmakers are complemented by a developed ecosystem of more than 365 suppliers (Tier 1-3) across the country, with companies such as Mobis, ZF, Schaeffler, Lear and Faurecia dominating [31].

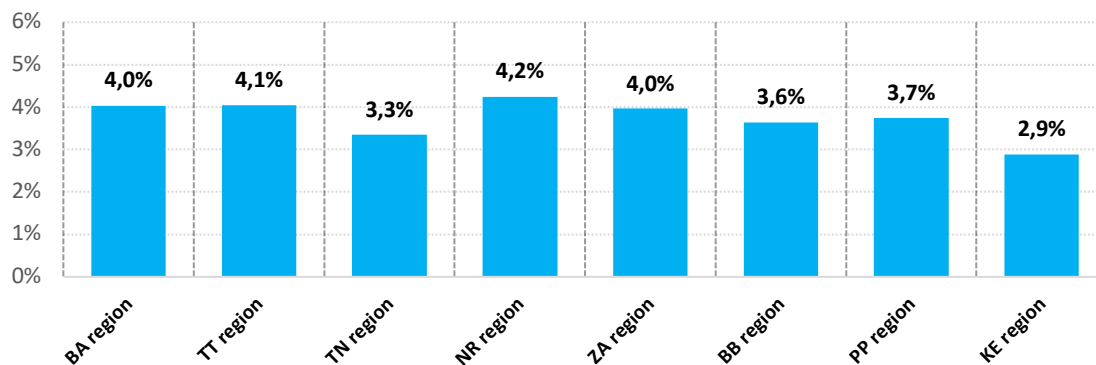
Table 1 List of active car manufacturers in Slovakia, 2025

Manufacturer	HQ location	In Slovakia since	Turnover (2023)	Number of employees (FTE, 2023)	Maximum load on electric grid (2024)
VOLKSWAGEN SLOVAKIA, a.s.	Bratislava (BA)	1991	€ 11,76 bill.	10 420	40 MW
PCA Slovakia, s. r. o.	Trnava (TT)	2003	€ 3,28 bill.	3 344	15 MW
Kia Slovakia s. r. o.	Žilina (ZA)	2004	€ 8,01 bill.	3 579	15 MW
Jaguar Land Rover Slovakia s. r. o.	Nitra (NR)	2015	€ 0,373 bill.	4 808	12 MW

Source: Register of Financial Statements of Slovakia, 2023 data (electricity load 2024).

Figure 5 presents the first day inoperability of automotive sector by various scenarios are presented. This metric (unlike economic losses) does not vary with blackout duration or it’s occurrence, so it provides valuable tool for assessing and comparing sectoral vulnerability to blackout.

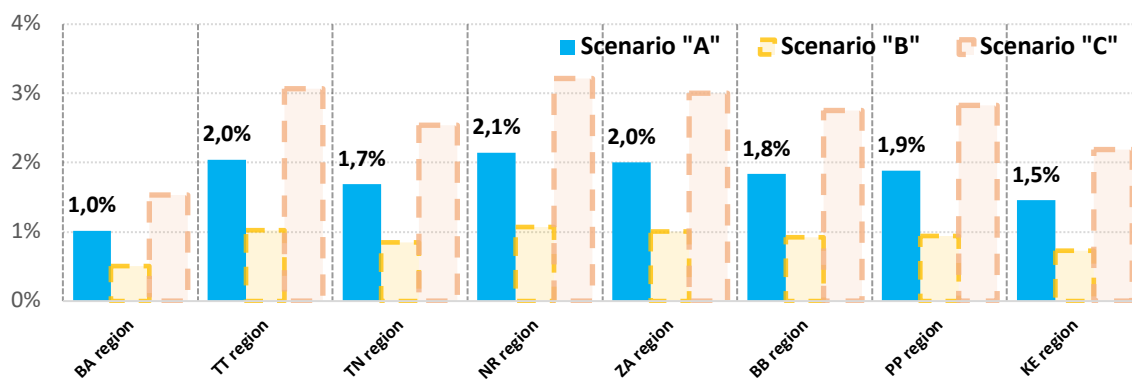
Figure 5 First day inoperability of automotive sector within Slovak economy



Source: own elaboration, based on structure of Slovak economy as of year 2022, Exiobase, ŠÚ SR

The biggest inoperability could be expected in a region Nitra (4,2% of production not realised) in the first day of total blackout. This region is closely followed by region of Trnava, with 4,1% rate of inoperability. The least affected would be Košice region, with only 2,9% of inoperability. For comparison, overall average inoperability for whole economy, weighted for production differences among regions and sectors is 10%.

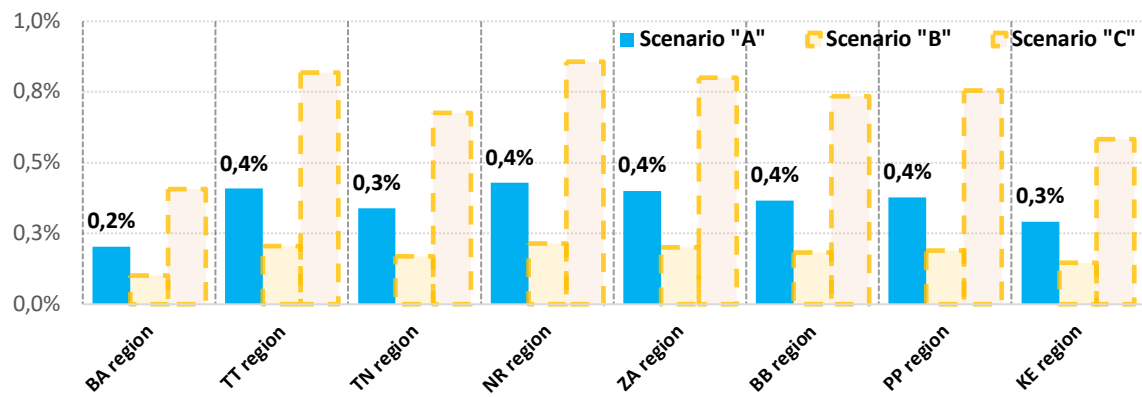
Figure 6 Second day inoperability of automotive sector within Slovak economy



Source: own elaboration, based on structure of Slovak economy as of year 2022, Exiobase, ŠÚ SR.

Mainly due to prioritised recovery in region of Bratislava, this region will resume its operability at the fastest pace, dropping in inoperability by 3 p. p. between the first and second day of blackout.

Figure 7 Third day inoperability of automotive sector within Slovak economy



Source: own elaboration, based on structure of Slovak economy as of year 2022, Exiobase, ŠÚ SR

Unsurprisingly, most significant inoperability would be recorded by propositions of the least optimistic scenario of recovery path, the Scenario “C”. In this scenario, where only 25% of electricity supply would be recovered during the second day, inoperability in second day reaches 3,2% in most affected Nitra region, compared with 2,1% in Scenario “A” and 1,1% in Scenario “B” respectively.

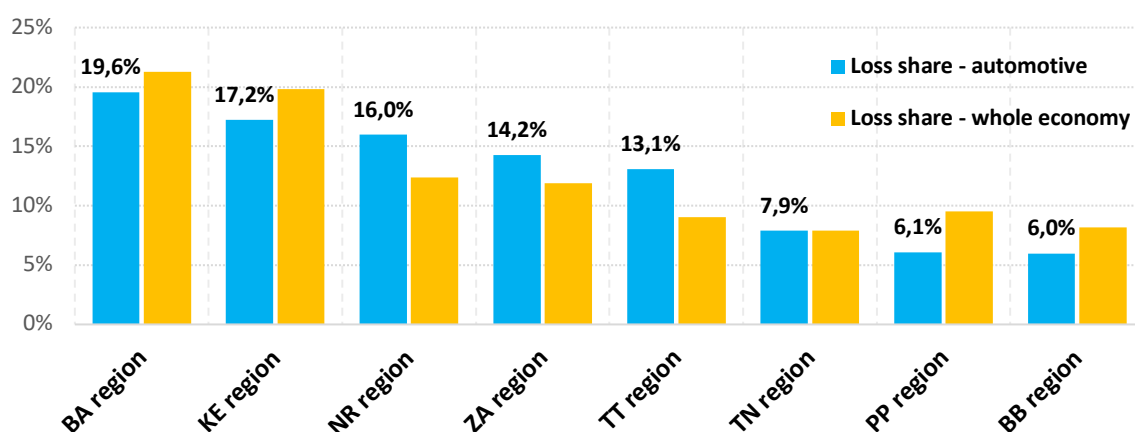
Below we summarize economic impacts on automotive industry and total economy by means of final demand losses, production losses, and hours worked. The most significant impacts to automotive sector will be incurred to in the scenario of slow recovery with blackout occurrence during winter morning. Impacts on final demand of the whole economy could be as low as € 34.28 mil., representing a situation in which blackout occurs during summer afternoon in rapid recovery Scenario “B,” to as high as € 122.49 mil. within slow recovery Scenario “C” and blackout occurrence at winter morning. This value represents as much as 10% of final demand of the three days of blackout duration. Relative losses would be biggest during the first day of blackout, when this day economic damage would reach up to 16.4% of daily final demand. Within the same scenario, production losses oscillate from € 50.08 mil. to € 181.84 mil., while loss of hours worked reaches up to 1.38 million and 5.17 million hours of working time, respectively.

Impacts on final demand of automotive sector range from € 2.12 mil. (4.2%) incurred, if blackout occurs during winter afternoon in rapid recovery Scenario “B” to as high as € 5.62 mil. (4.6%) within slow recovery Scenario “C” and blackout at occurrence at winter morning. Within the same scenario configuration, production losses oscillate from € 3.15 mil. to € 8.38 mil., while loss of hours worked reaches up to 10.4 thousand and 27.6 thousand hours of working time, respectively. Please note remarkably interesting fact - the different severity of the individual scenarios for the automotive sector and the total economy. A common feature is, that the least severe effects are

observed within recovery scenario B. However, from temporal point of view, the mildest impact for whole economy is seen within summer scenario on Saturday afternoon of September 10th, whereas for automotive sector it is winter scenario on Tuesday afternoon of January 18th. The explanation may be found in continuous, shift-operation of automotive sector within a period of the year that is not subject to the September, lower electricity consumption pattern, characteristic for the rest of the economy. However, it is essential to note that because of the characteristic temporal changes of the automotive sector's output, this impact could also be exactly the opposite - see Figure 3 - if the blackout were modelled during July or August, the plan-wide holidays in the automotive sector during this period would contribute to reducing the impact. This difference could be significant, as their impact causes a reduction in output during these months of up to 15 and 17 percentage points respectively (July and August 2022 in Figure 3).

Thought this comparison we can easily see the relative resilience of automotive industry, compared to rest of economy. While this sector is accounting for 9.8% of total production of Slovak economy, it is hit by only 4.2% to 4.6 % of economic losses induced in whole economy. Next, we closer present regional and temporal distribution of losses both in automotive industry and whole economy. Due to the limited space of the paper, we present in more detail the results for scenario “A” - winter-morning. We have chosen this recovery path, because we consider it a middle, most probable development option.

Figure 8 Proportion of estimated regional final demand losses on national losses within automotive sector and whole economy for Scenario A – blackout at 8th of January 2022, morning (total amount for all days)



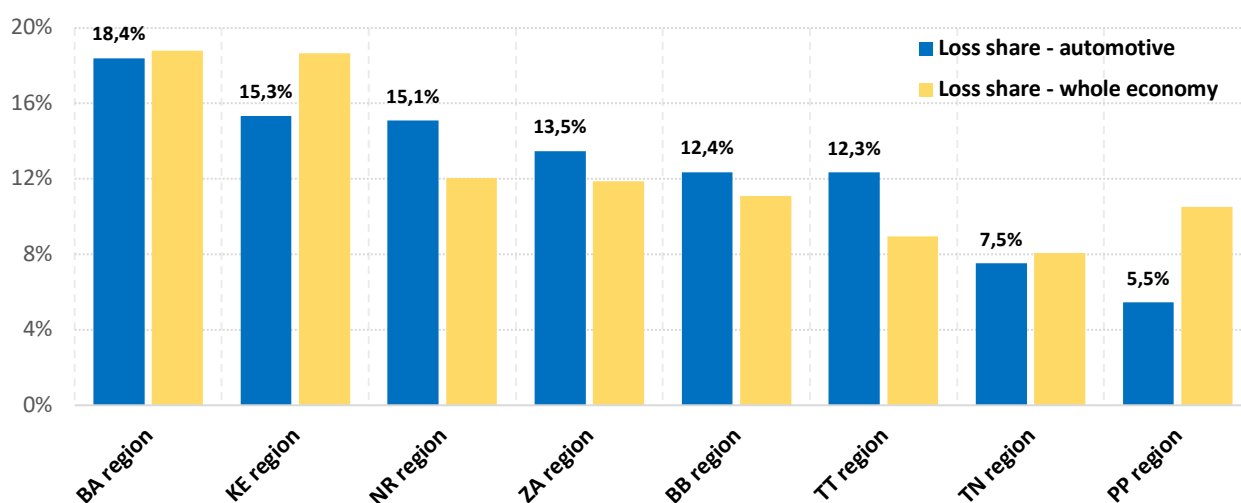
Source: own elaboration, Exiobase, ŠÚ SR, based on structure of Slovak economy as of year 2022.

The figure above presents the distribution of final demand losses of automotive industry and whole economy on regional level within the selected scenario. It is clear that the regions that have been most severely affected are not necessarily identical to those that have suffered the largest losses. The

most significant share of the total losses, up to 21%, would be present in the Bratislava region (19.6% within the automotive). Conversely, the lowest share, only 8% and 6% respectively within the automotive, would be in the Banská Bystrica region. An interesting finding is that regions with a significant presence of the automotive sector such as BA, KE, NR, and ZA achieve higher shares also in terms of the share of whole economy losses, and also that disproportionately higher automotive sector shares (in relation to whole) occur in the NR, ZA and TT regions (3 p.p, 2.2 p.p and 4.1 p.p. difference) This is interesting, considering that regions with biggest automotive sector presence are BA (25%) and KE regions.

The biggest losses of automotive sector in all scenarios, 79% of total losses for all days, would be observed during the first day of blackout within prepositions of scenario “B”.

Figure 9 Share of estimated regional employment hours worked losses to total employment hour losses in automotive sector and whole economy for Scenario A – blackout at 18th of January 2022, morning (total amount for all days)



Source: own elaboration, Exiobase, ŠÚ SR, based on structure of Slovak economy as of year 2022

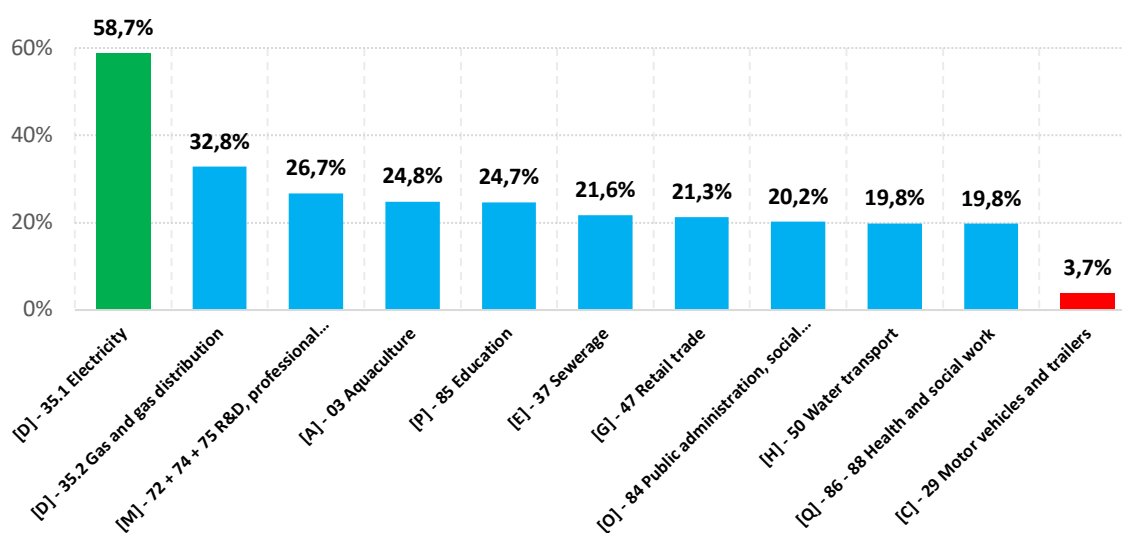
Considering scenario “A,” 65% of losses would be incurred during the first day, whereas in “C” it would be 54%. In the second day, scenario “C” represents the biggest impact, as well as loss share among scenarios considered. 36% of total losses for all days, accounting to 2,01 million of automotive final demand loss, would be observed within scenario “C” in second day. Considering scenario “A,” 29% of losses would be incurred, and in “B” it would be 17%. In third day, the least severe for all scenarios, shares of 10%, 6%, and 4% losses share would be observed for scenarios “C”, “A” and “B” respectively. Finally, we compare the share of regional losses in estimated hours worked to total employment hours lost in the automotive sector as well as in the economy as a whole. This comparison yields different results than the final demand survey. Interestingly, we can see a significant increase in

the share of hours not worked in the automotive industry in the Banská Bystrica region, relative to its share of final demand losses (6% versus 12.4%). This result is due to the specific intersectoral relations of the automotive sector in this region - since it is the cumulative effect of direct and indirect effects, it is likely that due to the lower presence of the industries that make up the automotive sector in this region, its import and labour intensity of partner sectors is increasing.

3.2 Sectoral Vulnerability and Evolution Over Time

In this subsection we focus on summarizing the vulnerability of the automotive sector based on the results presented above, as an assessment of the evolution of its vulnerability as well as the vulnerability of the economy to blackouts over time.

Figure 10 Comparison of average (all regions) sectoral inoperability among top 10 most blackout affected sectors and automotive industry by degree of sectoral inoperability, first day of blackout, all scenarios



Source: own elaboration, Exiobase, based on structure of Slovak economy as of year 2022.

Total inoperability in the economy, weighted by output across sectors, would have been 13.4% on the first day of the blackout; when weighted across sectors and regions, it is 10%. The most significantly affected sector in the event of a nationwide blackout would be the electricity sector itself, from which the disruption originates. As much as 58.7% of its output would be lost during the first day of the event. The Gas production and distribution sector would follow at a significant distance with 32.8%, followed by the Research, development, and professional activities sector. Surprisingly, the second least affected sector would be the Automotive, which would have an average inoperability rate among the regions of only 3.7%.

Conclusion

We document relative economic resilience of the automotive sector to effects of locally limited and short-term blackout. Even in the most severe case (Scenario C, blackout occurrence at winter morning), the total final demand loss in Automotive sector as result of three-day blackout remains contained at € 5.62 mil., representing 4.6% of the national economic loss of € 122.49 mil. Similarly, the most optimistic scenario for Automotive sector (Scenario B, winter afternoon) yields a sectoral loss of € 3.15 mil. of production (4.2% of national losses). In addition, blackout could cause the total loss of 5.17 mil. employment hours worked, 27.6 thousand of which (0.53%) would be in automotive sector. These estimates represent the grand total of a 10 % loss of final demand and production and 0.09% loss of working hours at the national level due to the blackout.

At the regional level, the analysis highlights pronounced heterogeneity: regions with concentrated Automotive activity, notably Bratislava and Košice, bear the greatest absolute losses, although not experiencing the biggest inoperability within regions. By means of production inoperability, the most seriously affected regions during the blackout event would be the Nitra region, with 4.2% of automotive sector inoperability in the first day of blackout. However, even this poses a significantly low rate of inoperability, given that the second most affected Gas and gas distribution sector (after electricity sector) in same region would experience inoperability as high as 37.8%.

Methodologically, the integration of daily and seasonally adjusted electricity-load indices alongside industry-specific production indices represents a significant advancement over basic static Input-Output approaches, capturing both short-term consumption peaks and longer-term production cycles. The analytical framework developed herein offers a flexible, replicable tool for policymakers and industry stakeholders. The main benefits include the high regional resolution of the model at the NUTS level 3, which allows for quantification of losses in individual regions, as well as the flexibility of accruals (hourly/daily indices of electricity consumption and monthly indices of industrial production). A fully replicable Python-based analytical framework has been developed, that is open to further extensions and integration of new data sources or methodological modules. The model has extensive possibilities of further use. Stakeholders – from state authorities to the private sector – can flexibly model with the same level of detail the economic impacts of the blackout for other sectors, day-time of the occurrence and duration of the blackout as well as recovery paths. By replacing the automotive sector with alternative critical industries - such as energy-intensive steel manufacturing, or for society important sectors as food processing, or healthcare - stakeholders can rapidly assess blackout risks across the broader economic landscape.

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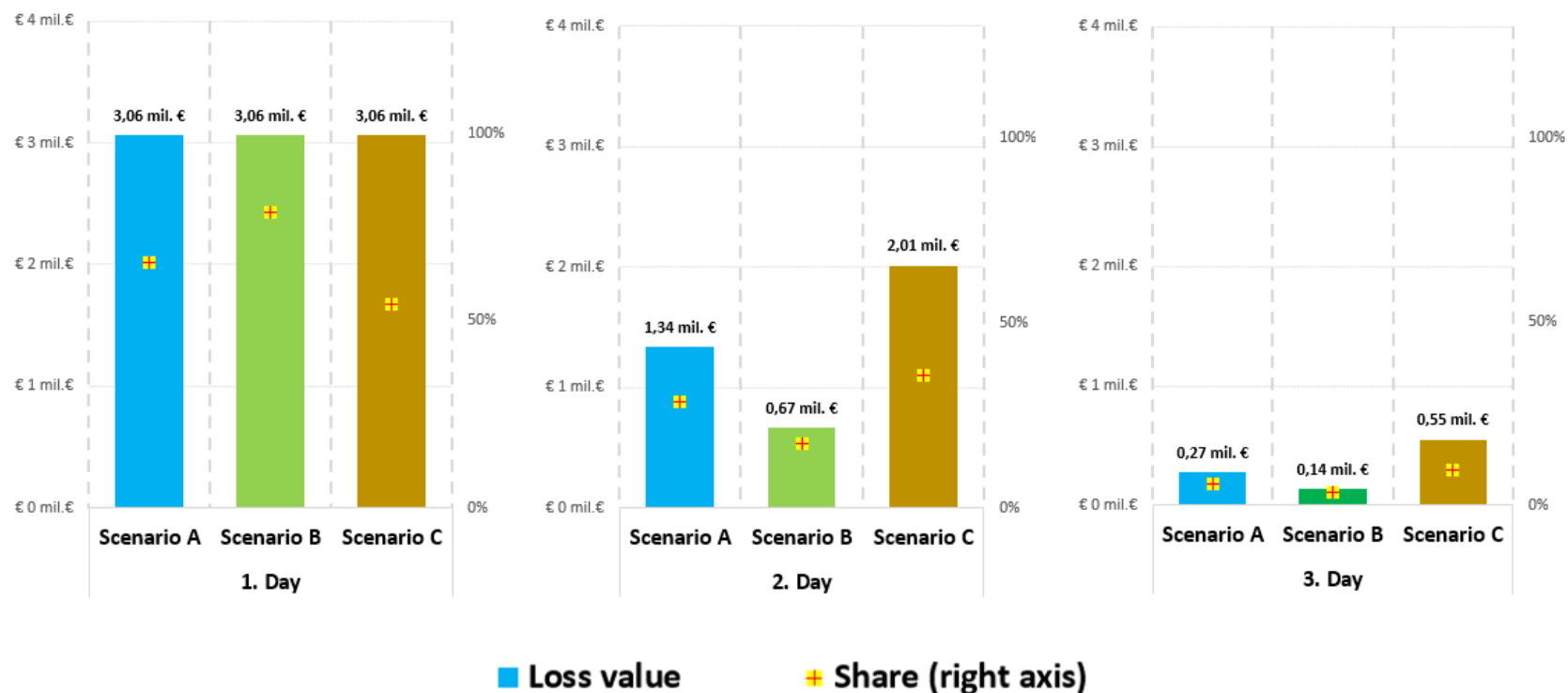
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Appendix

Figure A1 Loss of final demand suffered by automotive sector on day 1, day 2 and day 3 of blackout (left axis) and share on total three-day loss (right axis), blackout occurrence during 18th of January 2022



Source: own elaboration, Exiobase, ŠÚ SR, based on structure of Slovak economy as of year 2022

Source: own elaboration, Exiobase, ŠÚ SR, based on structure of Slovak economy as of year 2022

Source: own elaboration, Exiobase, ŠÚ SR, based on structure of Slovak economy as of year 2022