200 ÉVES A MAGYAR TUDOMÁNYOS AKADÉMIA

A szaharai porviharos események fotovoltaikus energiatermelésre és menetrendezésre gyakorolt egyre kifejezettebb hatásai

VARGA GYÖRGY*, GRESINA FRUZSINA, GELENCSÉR ANDRÁS, ROSTÁSI ÁGNES

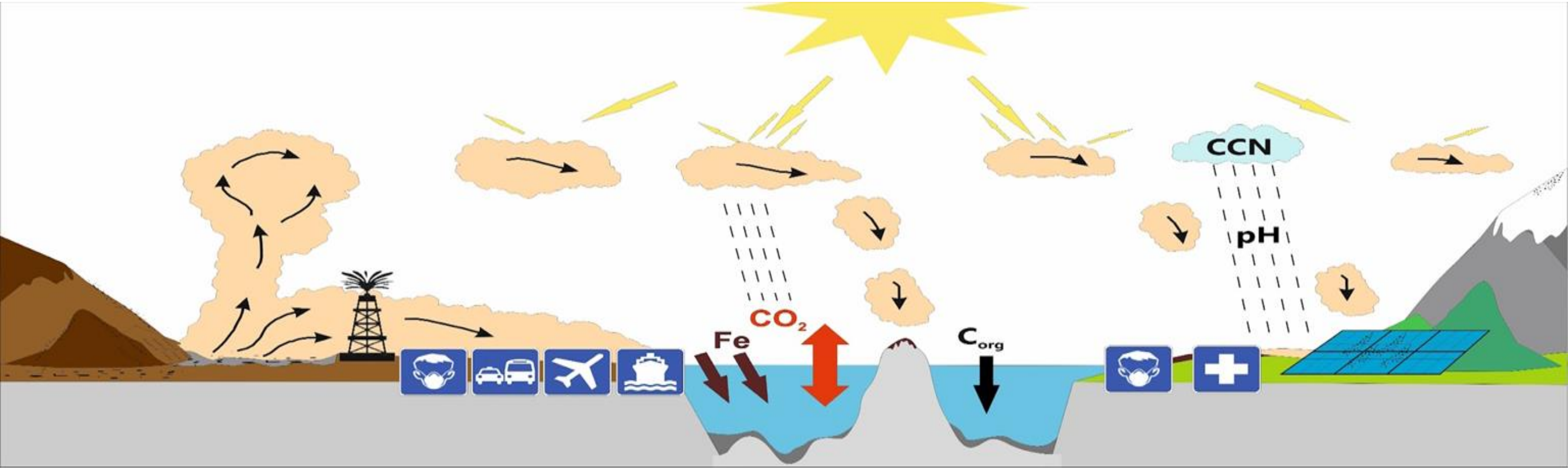
*tudományos főmunkatárs, HUN-REN Csillagászati és Földtudományi Kutatóközpont

2025. december 4.

MTA

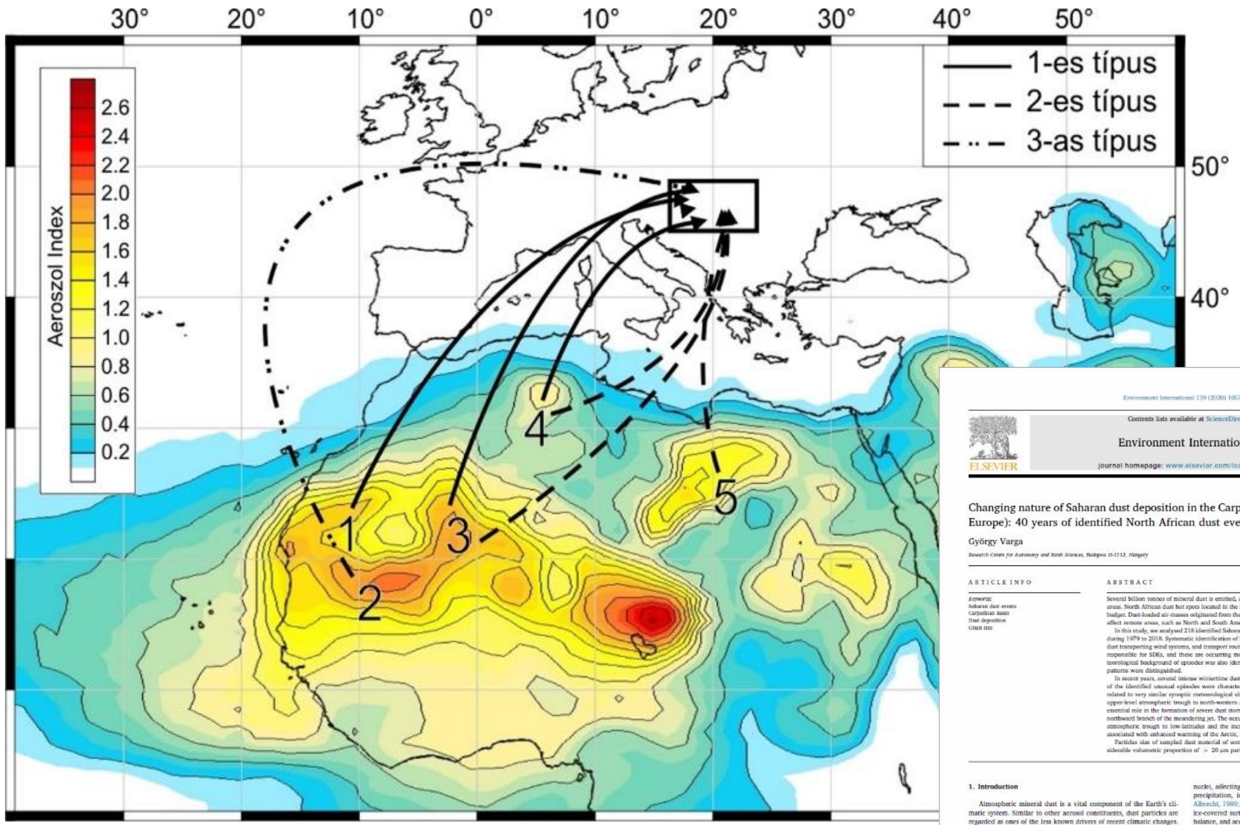
Miért érdekes a por?

- szél által légkörbe jutatott ásványi por mennyisége: **1-3 milliárd tonna évente (50-70% a Szaharából)**
- közvetlen és közvetett **klimatikus hatások** (besugárzás, CO2, felhőképződés)
- egyéb **környezeti hatások** (pH; talajképződés; egészségügyi hatások stb.)
- múltbéli változások **archívuma:** löszképződés és egyéb **hullóporos eredetű üledékek**
- számos **társadalmi és gazdasági** folyamatot szintén befolyásol



Szaharai por a Kárpát-medencében

- **290 szaharai porviharos eseményt** azonosítottunk a Kárpát-medencében az 1979-2025 időszakban (**NASA TOMS and OMI Aeroszol Index**) műholdas adatok alapján (**BSC DREAM8b v1.0 és v2.0** numerikus szimulációk hasonló eredményeket mutatnak a gyakoriságra vonatkozóan)
- **HYSPLIT trajektóriákat** használtunk a szaharai eredet megerősítése céljából
- 700 hPa geopotenciál szint, zonális és meridionális szélkomponensek és szélvektorok kerültek felhasználásra a **szinoptikus meteorológiai** helyzetek megállapításához
- **száraz és nedves kiülepedés** meghatározására a NASA Modern-Era Retrospective analysis for Research and Applications, Version 2 (**MERRA-2**) modelleredményeit használtuk




Environment International 139 (2020) 105712

Environment International

Changing nature of Saharan dust deposition in the Carpathian Basin (Central Europe): 40 years of identified North African dust events (1979–2018)

György Varga

Varga, Gy. (2020). *Changing nature of Saharan dust deposition in the Carpathian Basin (Central Europe): 40 years of identified North African dust events (1979–2018).* **Environment International** 139. 105712

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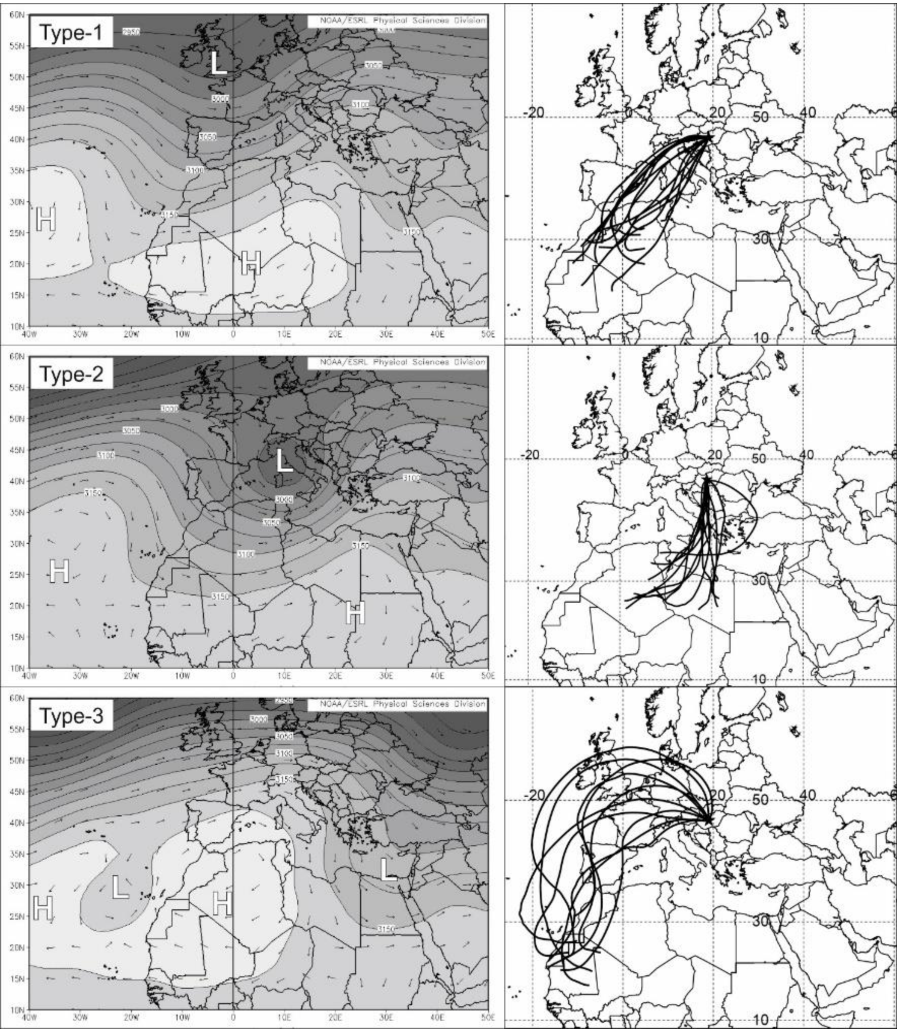

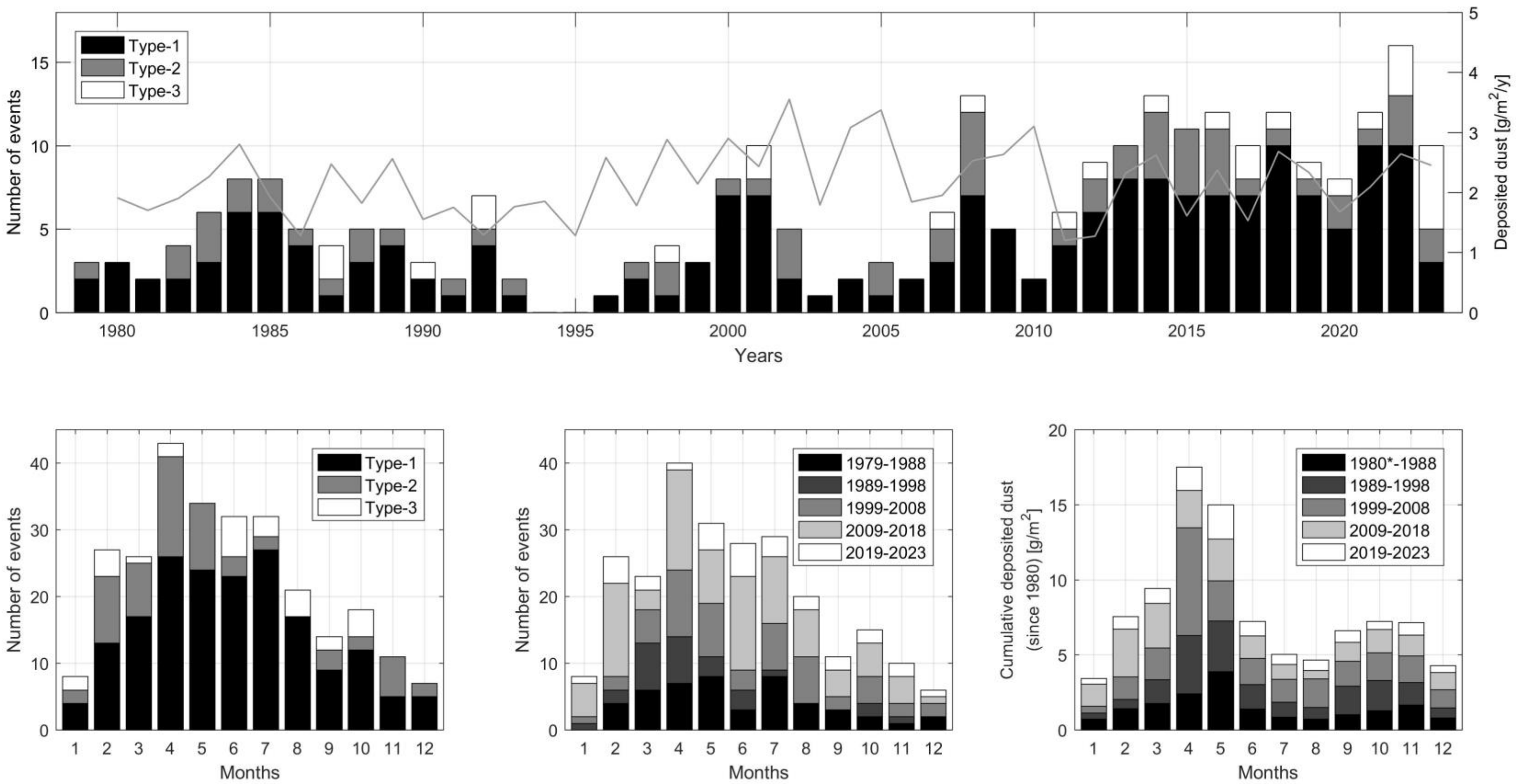

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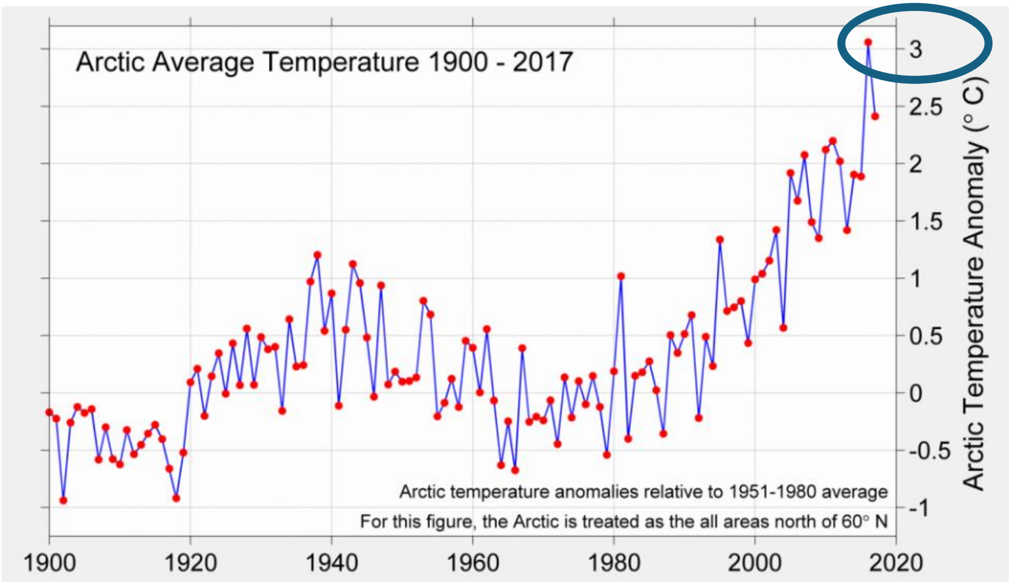
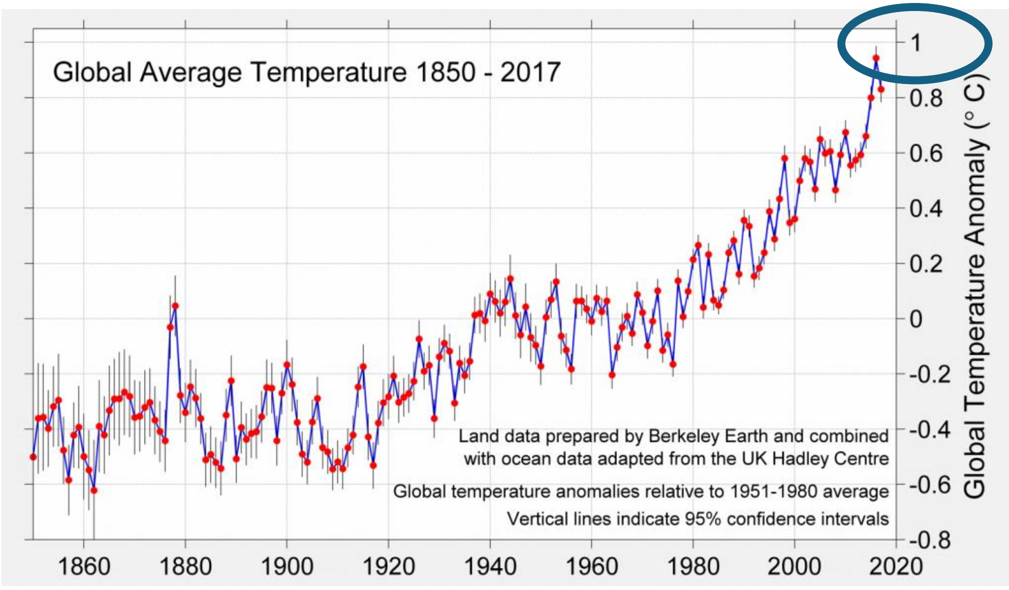
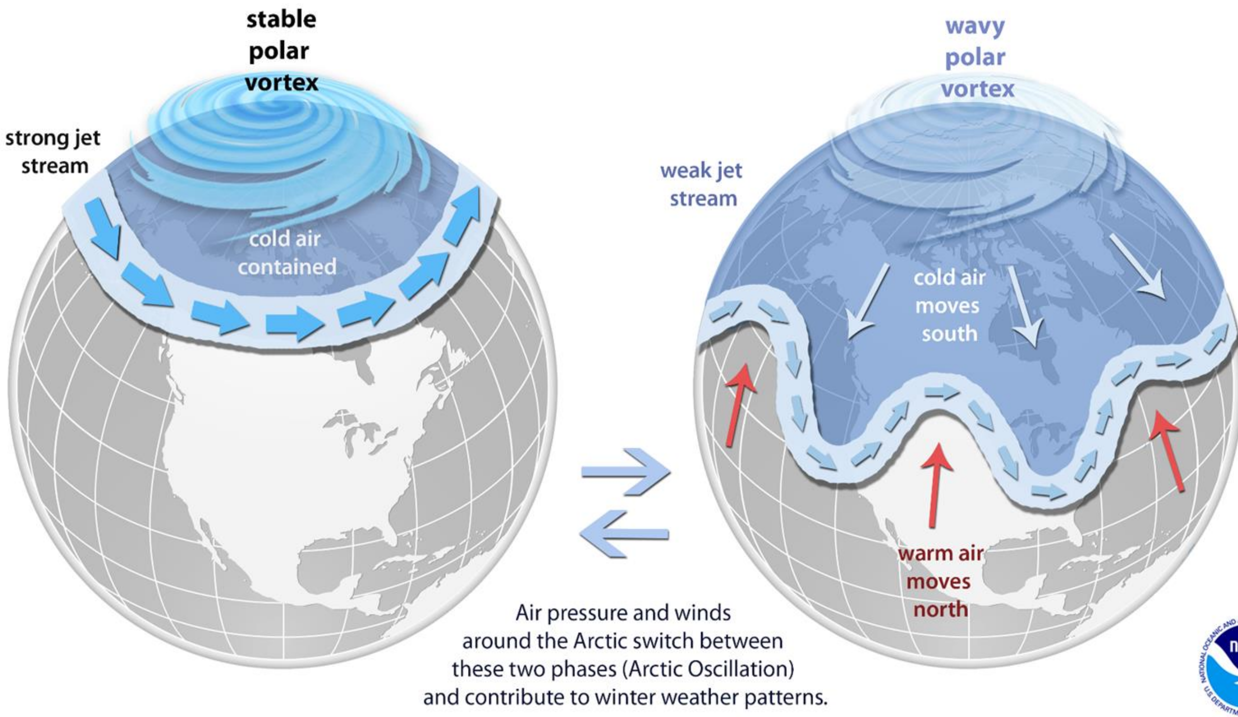




DOI: 10.15201/hungeobull.72.4.1 Hungarian Geographical Bulletin **72** 2023 (4) 319–337.

Increasing frequency and changing nature of Saharan dust storm events in the Carpathian Basin (2019–2023) – the new normal?

György VARGA[1,2,3], Ágnes ROSTÁSI[2,4], Aida MEIRAMOVA[2,4], Pavla DAGSSON-WALDHAUSEROVÁ[5,6] and Fruzsina GRESINA[1,3]



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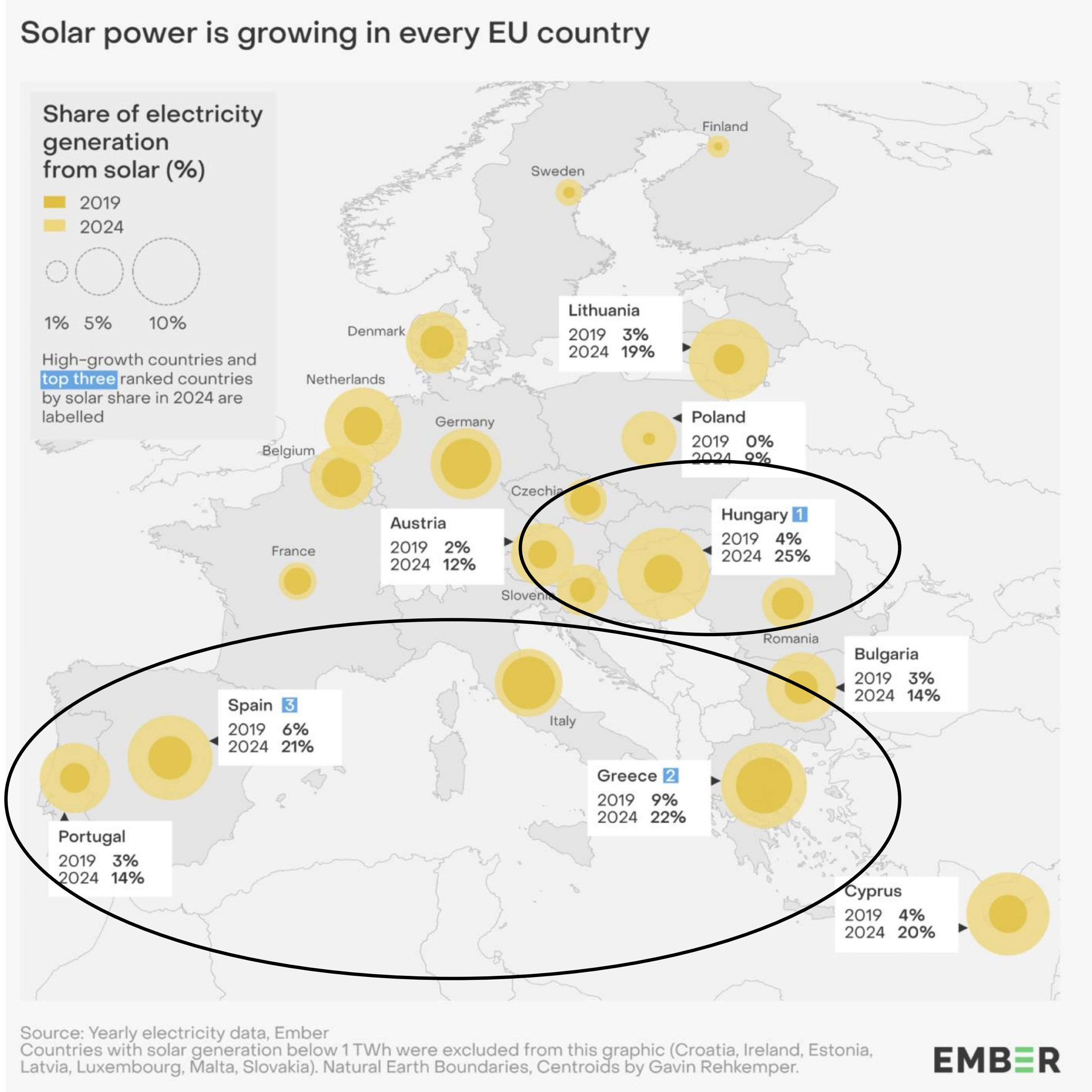

Atmos. Chem. Phys., 24, 4083–4104, 2024
https://doi.org/10.5194/acp-24-4083-2024

Atmospheric Chemistry and Physics

Sharp increase in Saharan dust intrusions over the western Euro-Mediterranean in February–March 2020–2022 and associated atmospheric circulation

Emilio Cuevas-Agulló[1,☆], David Barriopedro[2], Rosa Delia García[1,3], Silvia Alonso-Pérez[4,5], Juan Jesús González-Alemán[6], Ernest Werner[7], David Suárez[8], Juan José Bustos[1], Gerardo García-Castrillo[7], Omaira García[1], África Barreto[1], and Sara Basart[9,a]

Atmos. Chem. Phys., 24, 12031–12053, 2024
https://doi.org/10.5194/acp-24-12031-2024

Atmospheric Chemistry and Physics

Extreme Saharan dust events expand northward over the Atlantic and Europe, prompting record-breaking PM_{10} and $PM_{2.5}$ episodes

Sergio Rodríguez and Jessica López-Darias

Environment International 139 (2020) 105712
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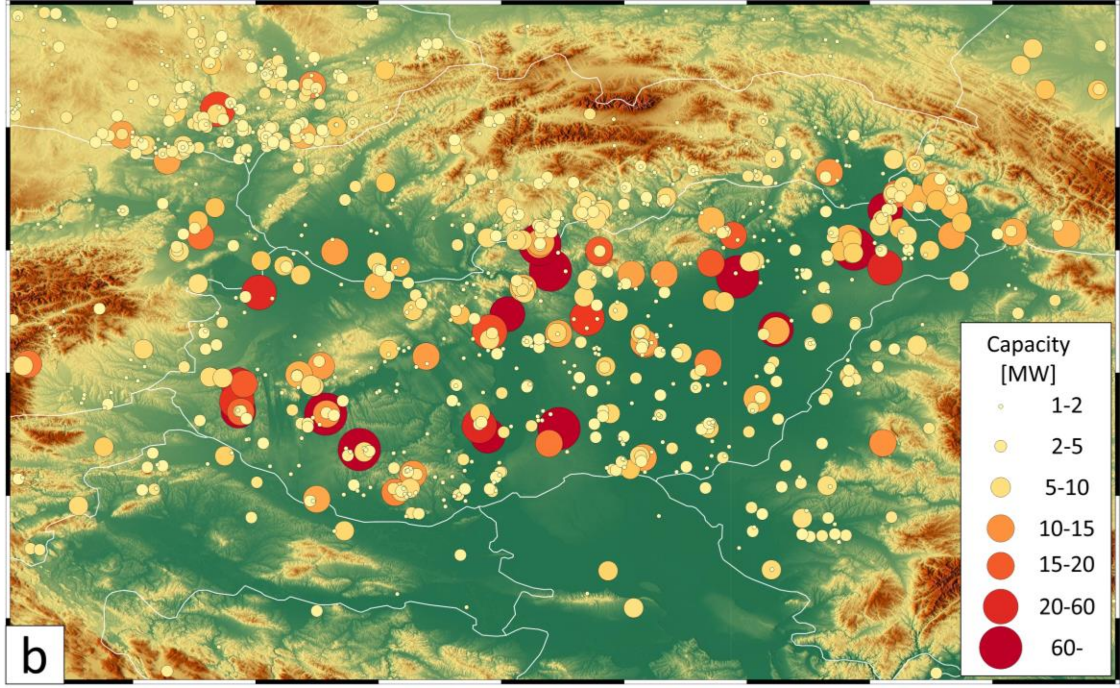
Changing nature of Saharan dust deposition in the Carpathian Basin (Central Europe): 40 years of identified North African dust events (1979–2018)

György Varga
Research Centre for Astronomy and Earth Sciences, Budapest H-1112, Hungary

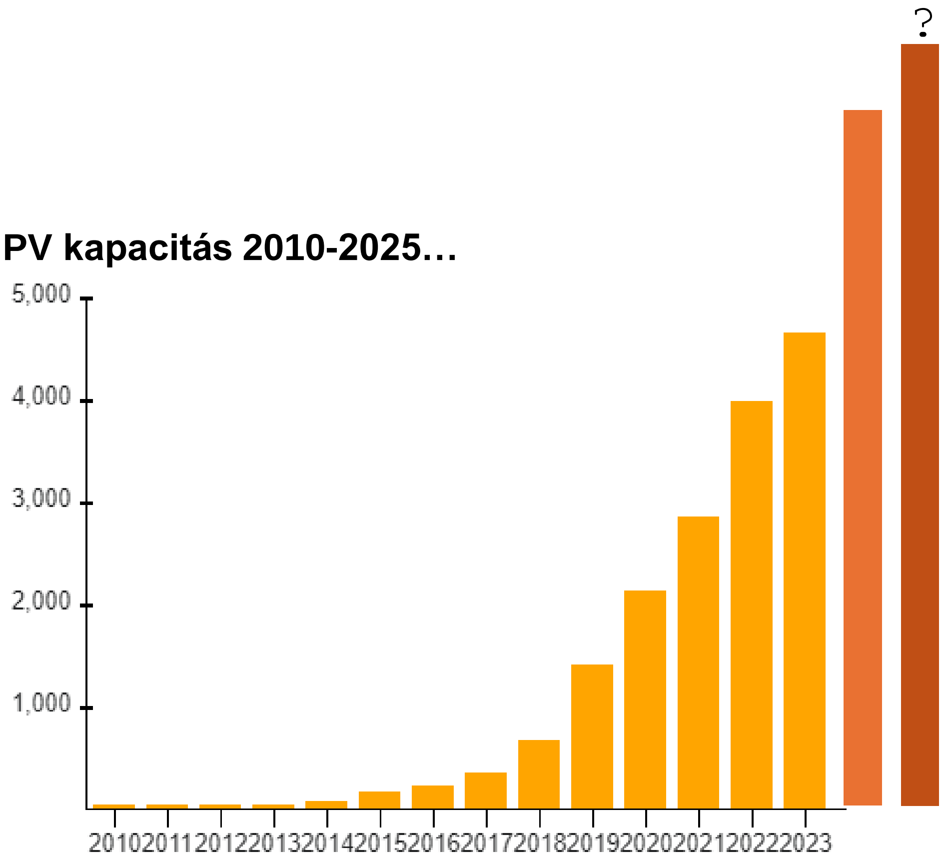
HUNGARIAN GEOGRAPHICAL BULLETIN

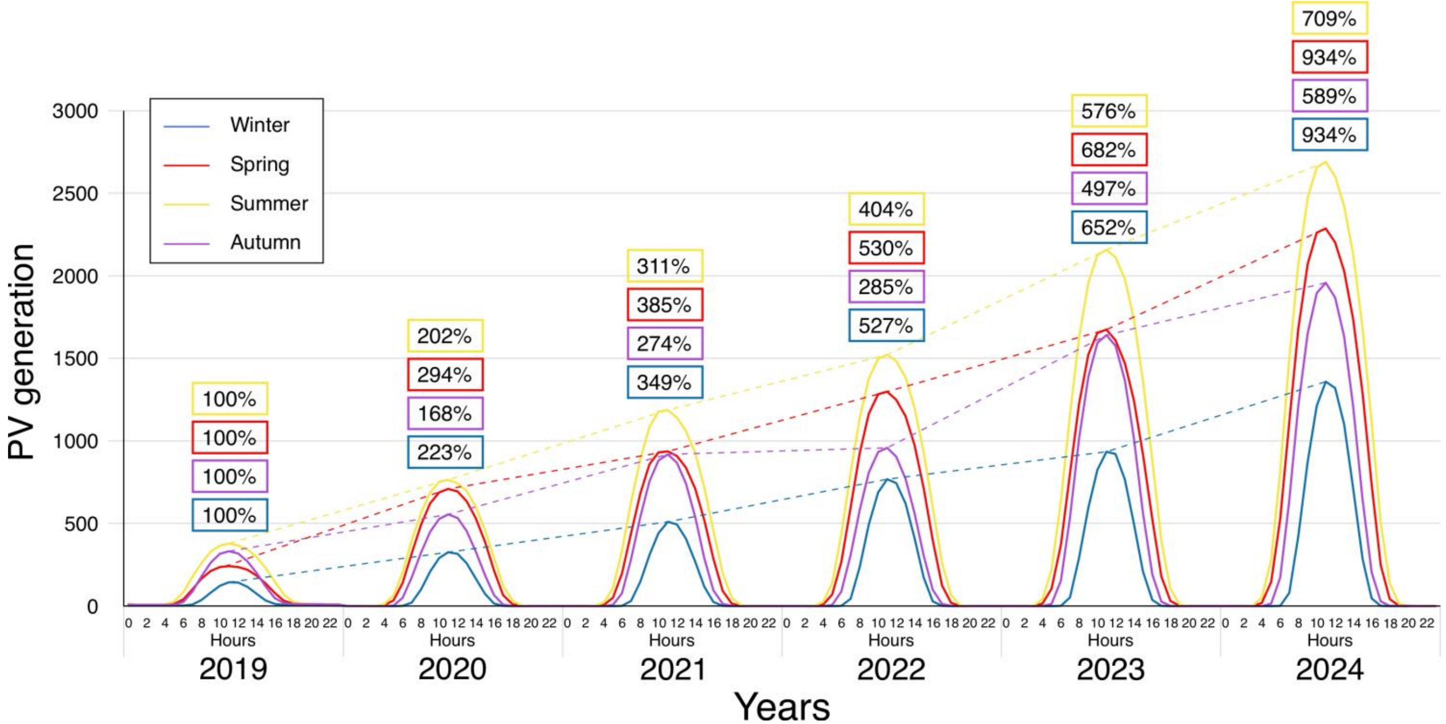
Increasing frequency and changing nature of Saharan dust storm events in the Carpathian Basin (2019–2023) – the new normal?

Fotovoltaikus energia Magyarországon



PV kapacitás 2010-2025…





A szaharai por és a fotovoltaikus energiatermelés

Renewable and Sustainable Energy Reviews 193 (2024) 114289

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Effect of Saharan dust episodes on the accuracy of photovoltaic energy production forecast in Hungary (Central Europe)

György Varga [a,b,c,d,*], Fruzsina Gresina [a,c,d], József Szeberényi [a,d], András Gelencsér [c,e], Ágnes Rostási [c,e]

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A R T I C L E I N F O

Keywords:
Solar panels
Photovoltaic energy
Saharan dust episodes
Accuracy
Energy production forecast

A B S T R A C T

In order to meet global sustainability goals, in particular, the rapid decarbonisation of the energy sector in combination with geopolitical energy security issues, as well as further improvement in regional air quality-the so-called renewable energy sources are becoming increasingly critical and important. Photovoltaic power (PV) generation is clearly the most widely deployed (non-hydro) renewable energy source globally, which still has a significant growth potential in many countries, including Hungary.

However, due to the intermittent nature and the strong dependency of photovoltaic power production on meteorological factors, continuous adjustment of electric power in the electric grid is needed. This, in turn, requires the most accurate forecast of the photovoltaic energy to be produced in the ultra-short term (15 min) and short term (1 day) in order to minimise last-minute and high-price energy acquisition or unplanned kicks-in of gas-fired auxiliary power plants.

In this paper, we evaluate the impacts of large-scale dust transport episodes on the accuracy of forecasts of PV power generation. The numbers and intensities of Saharan dust storm events reaching Central Europe have increased over the last decade, hitting a new record in 2022 with 16 (!) African dust episodes observed over Hungary. We have shown that the semi-direct effect of atmospheric dust particles on high-level cloud formation rather than their direct irradiance-reducing effect is responsible for the reduced accuracies of e short-term (24-h) PV energy production forecasts during these events.

1. Introduction

The energy crisis, fuelled by mitigation-focused climate policy, sustainability concerns and global geopolitics, has fundamentally increased the importance of renewable energy production [1,2]. This is particularly true for countries with a high share of imported fossil fuels in their energy mix exposed to geopolitical risks [3,4].

Beyond the geopolitical energy crisis, renewable energy investments are of particular importance for the long-term prospects of zero-carbon policies. Because of the unresolved storage of electricity at a large scale, there must be a continuous balance between production and consumption of electric energy [5]. This means that it is vital to have the best possible estimate for electric energy production for the short-to-mid-term, which poses a great challenge for strongly weather-dependent renewables. Solar power forecasting is the process of predicting the expected solar power output from a photovoltaic (PV) system over a given time period. This process is important for energy system operators and utility companies who need to ensure that they can meet their consumers' demand for electricity by balancing the supply and demand of energy on the grid. Accurate forecasting is important not only for maintaining grid stability, reducing greenhouse gas emissions, and optimising operational costs. The latter includes heavy penalties imposed upon the difference between the forecast and the energy actually produced.

Proper forecasts can help utilities to reduce the need for kicking-in expensive gas-fired backup power plants and improve grid stability.

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E-mail address: varga.gyorgy@csfk.org (G. Varga).

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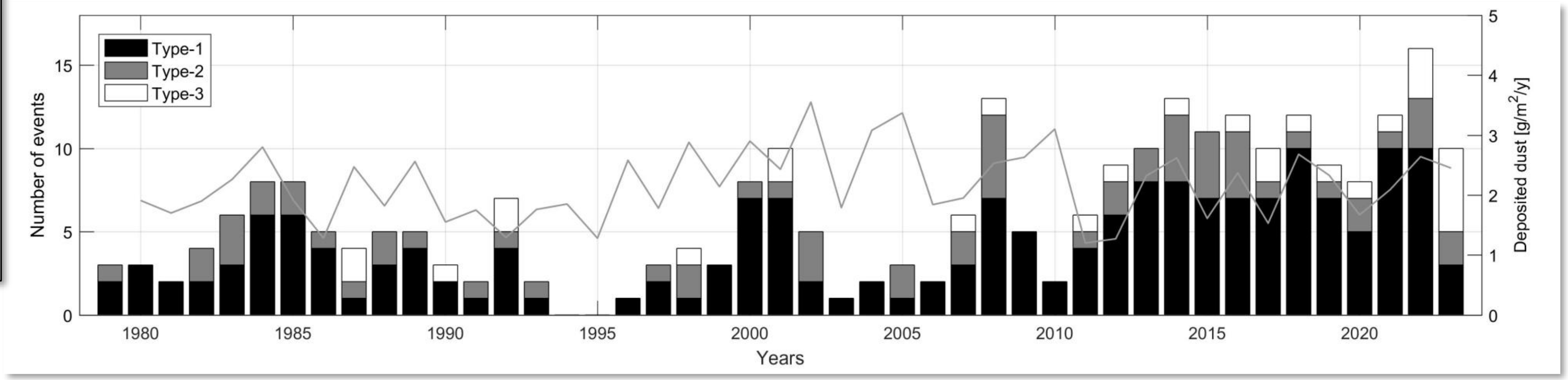
A **2022-es év** adatai alapján kerestünk kapcsolatot a szaharai porviharos események és a napelemes energiatermelés közt

2022-ben **16 (!) alkalommal** érte el Magyarországot szaharai poros légtömeg



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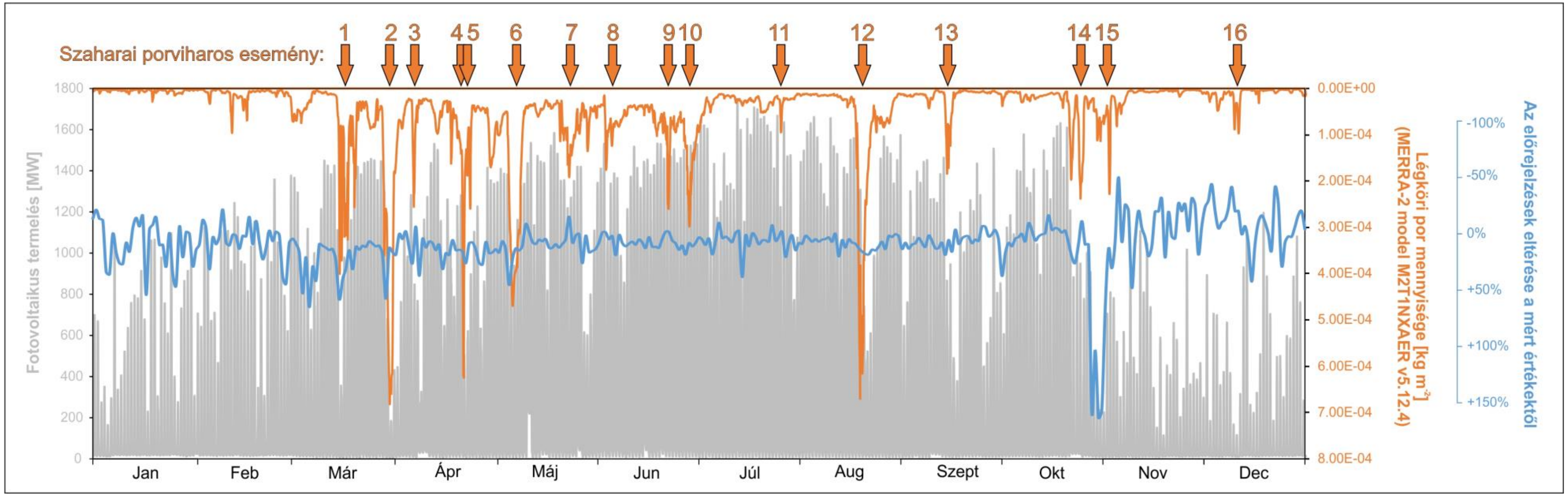

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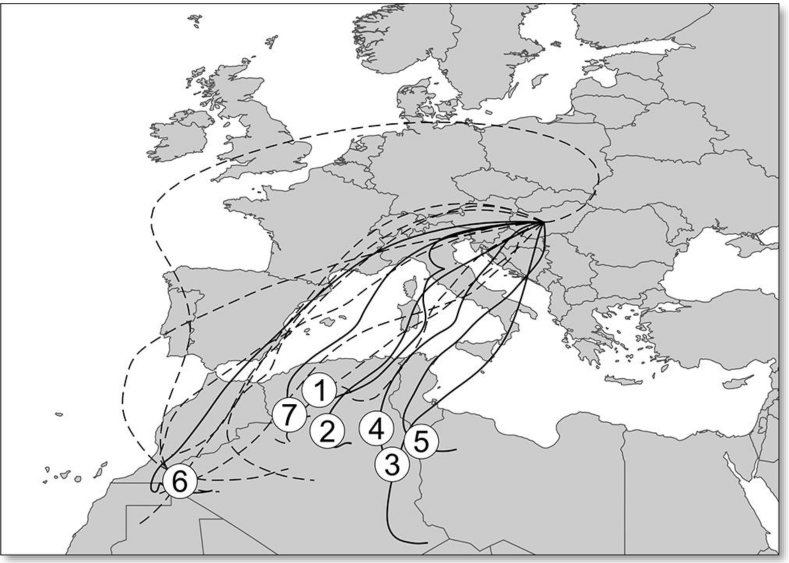

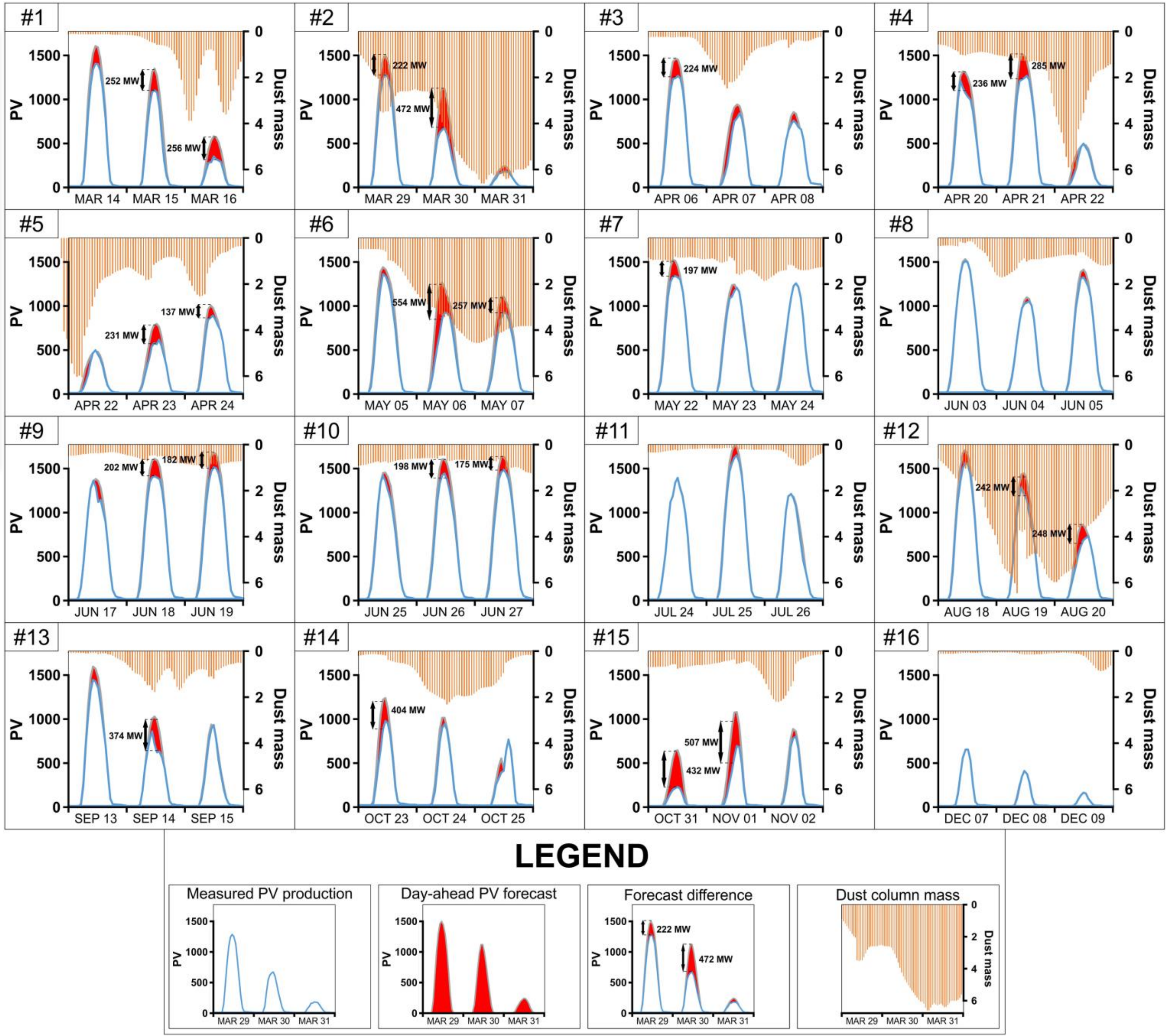

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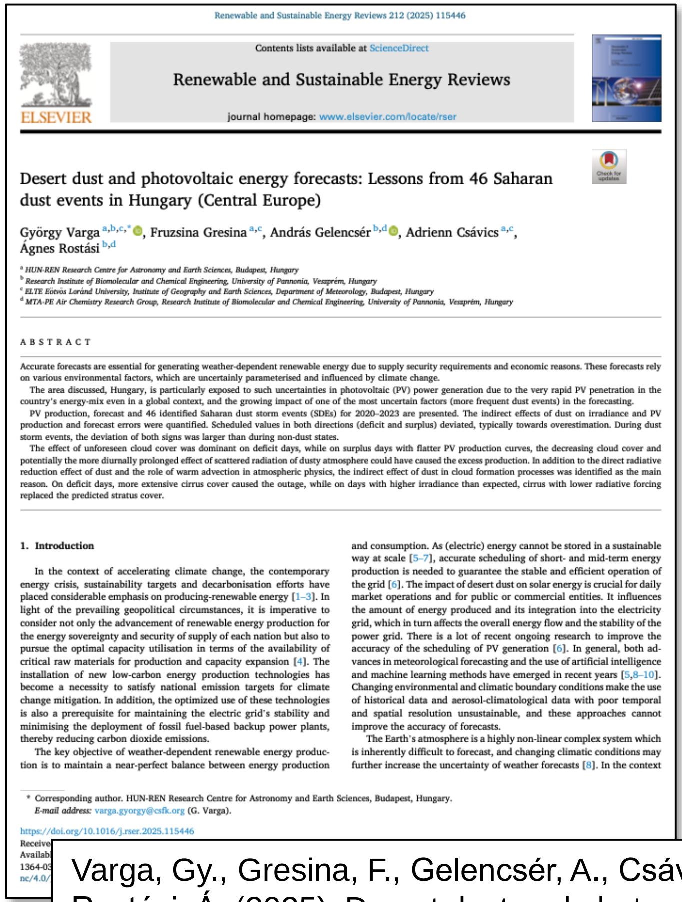

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Desert dust and photovoltaic energy forecasts: Lessons from 46 Saharan dust events in Hungary (Central Europe)

György Varga [a,b,c,*], Fruzsina Gresina [a,c], András Gelencsér [b,d], Adrienn Csávics [a,c], Ágnes Rostási [b,d]

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A B S T R A C T

Accurate forecasts are essential for generating weather-dependent renewable energy due to supply security requirements and economic reasons. These forecasts rely on various environmental factors, which are uncertainly parameterised and influenced by climate change.

The area discussed, Hungary, is particularly exposed to such uncertainties in photovoltaic (PV) power generation due to the very rapid PV penetration in the country's energy-mix even in a global context, and the growing impact of one of the most uncertain factors (more frequent dust events) in the forecasting.

PV production, forecast and 46 identified Saharan dust storm events (SDEs) for 2020–2023 are presented. The indirect effects of dust on irradiance and PV production and forecast errors were quantified. Scheduled values in both directions (deficit and surplus) deviated, typically towards overestimation. During dust storm events, the deviation of both signs was larger than during non-dust states.

The effect of unforeseen cloud cover was dominant on deficit days, while on surplus days with flatter PV production curves, the decreasing cloud cover and potentially the more diurnally prolonged effect of scattered radiation of dusty atmosphere could have caused the excess production. In addition to the direct radiative reduction effect of dust and the role of warm advection in atmospheric physics, the indirect effect of dust in cloud formation processes was identified as the main reason. On deficit days, more extensive cirrus cover caused the outage, while on days with higher irradiance than expected, cirrus with lower radiative forcing replaced the predicted stratus cover.

1. Introduction

In the context of accelerating climate change, the contemporary energy crisis, sustainability targets and decarbonisation efforts have placed considerable emphasis on producing-renewable energy [1–3]. In light of the prevailing geopolitical circumstances, it is imperative to consider not only the advancement of renewable energy production for the energy sovereignty and security of supply of each nation but also to pursue the optimal capacity utilisation in terms of the availability of critical raw materials for production and capacity expansion [4]. The installation of new low-carbon energy production technologies has become a necessity to satisfy national emission targets for climate change mitigation. In addition, the optimized use of these technologies is also a prerequisite for maintaining the electric grid's stability and minimising the deployment of fossil fuel-based backup power plants, thereby reducing carbon dioxide emissions.

The key objective of weather-dependent renewable energy production is to maintain a near-perfect balance between energy production and consumption. As (electric) energy cannot be stored in a sustainable way at scale [5–7], accurate scheduling of short- and mid-term energy production is needed to guarantee the stable and efficient operation of the grid [6]. The impact of desert dust on solar energy is crucial for daily market operations and for public or commercial entities. It influences the amount of energy produced and its integration into the electricity grid, which in turn affects the overall energy flow and the stability of the power grid. There is a lot of recent ongoing research to improve the accuracy of the scheduling of PV generation [6]. In general, both advances in meteorological forecasting and the use of artificial intelligence and machine learning methods have emerged in recent years [5,8–10]. Changing environmental and climatic boundary conditions make the use of historical data and aerosol-climatological data with poor temporal and spatial resolution unsustainable, and these approaches cannot improve the accuracy of forecasts.

The Earth's atmosphere is a highly non-linear complex system which is inherently difficult to forecast, and changing climatic conditions may further increase the uncertainty of weather forecasts [8]. In the context

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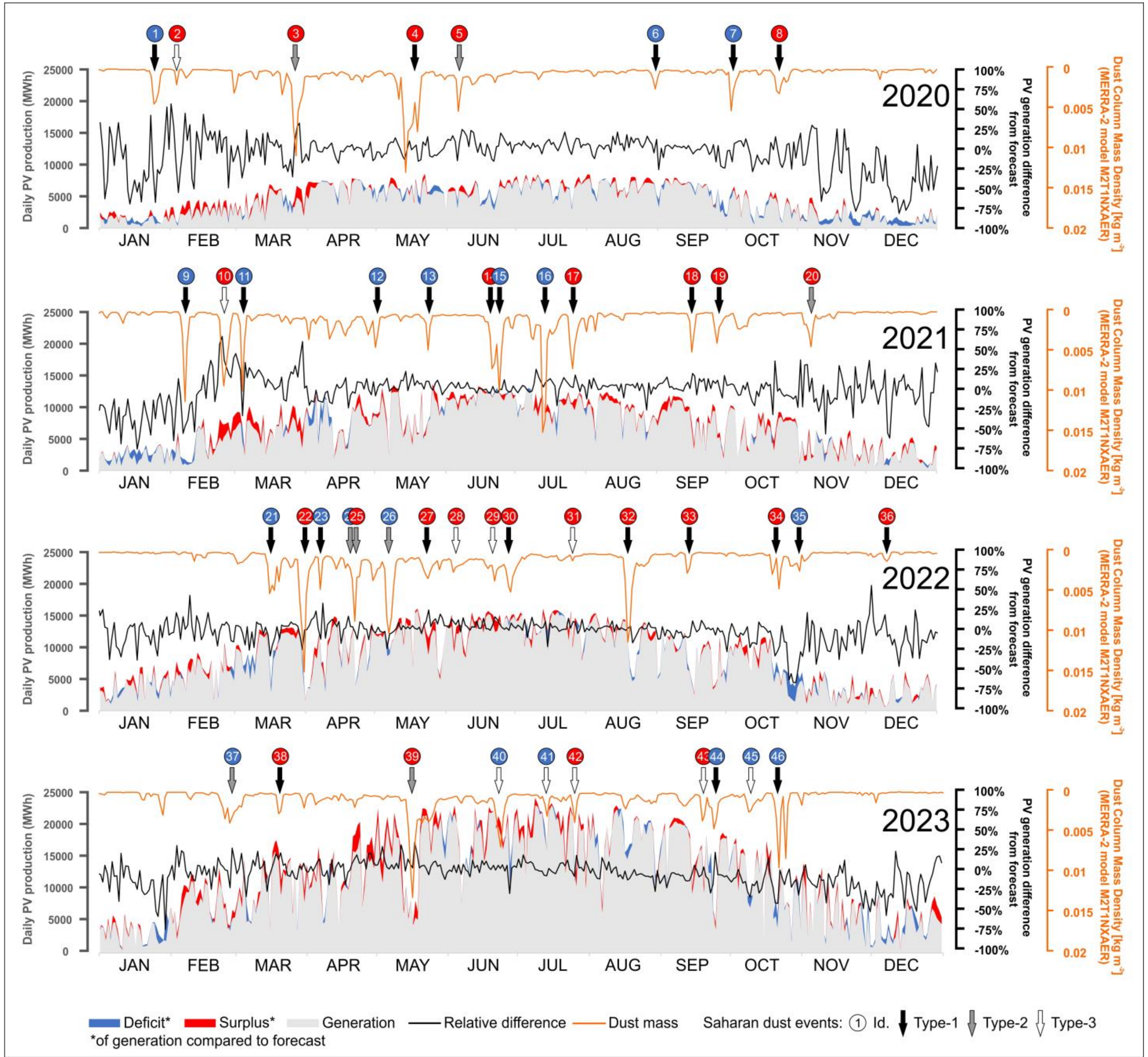
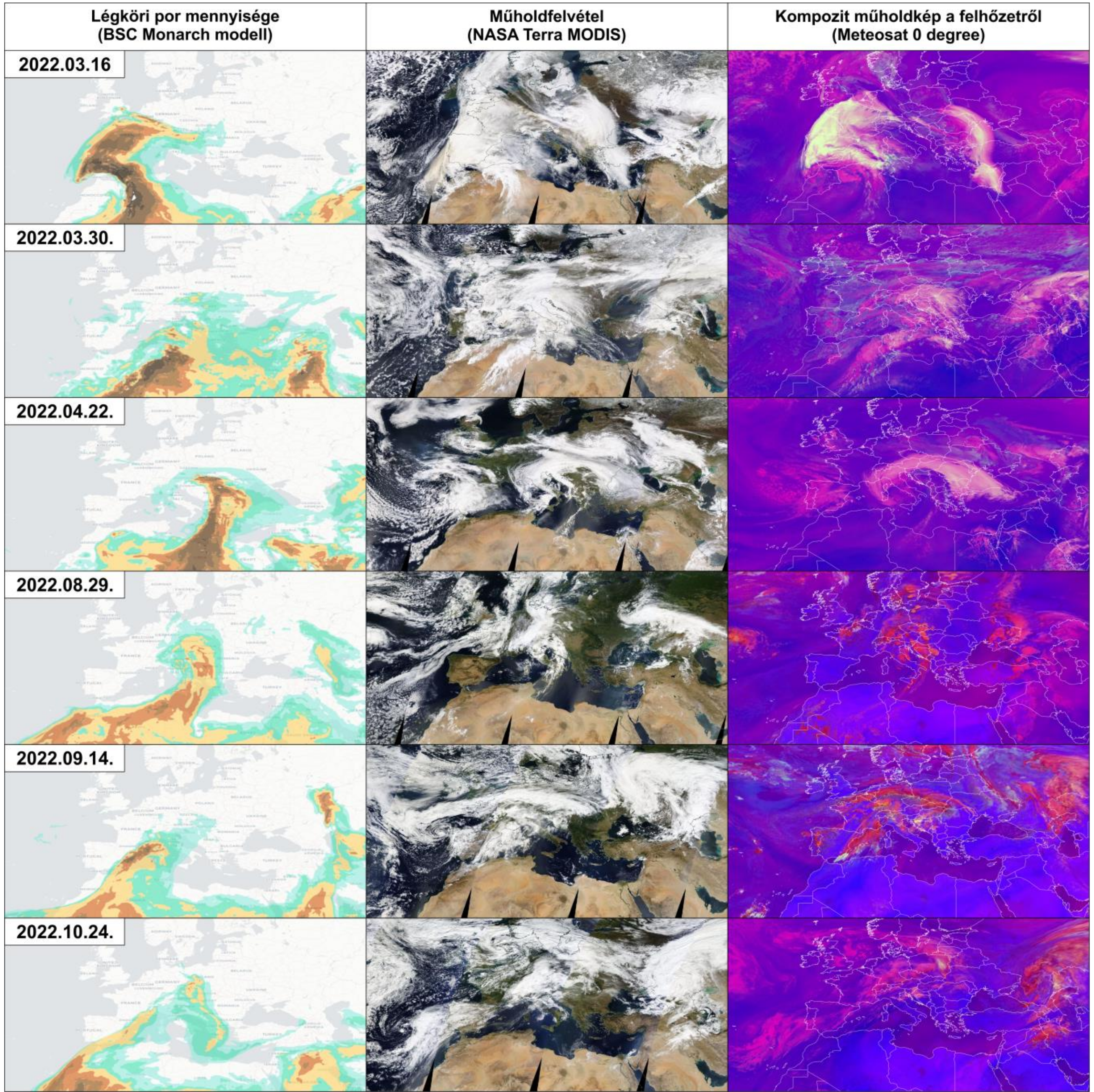


A szaharai por közvetett hatása: cirrusok?



HungaroMet Nonprofit Zrt.
March 1 at 8:59 AM ·

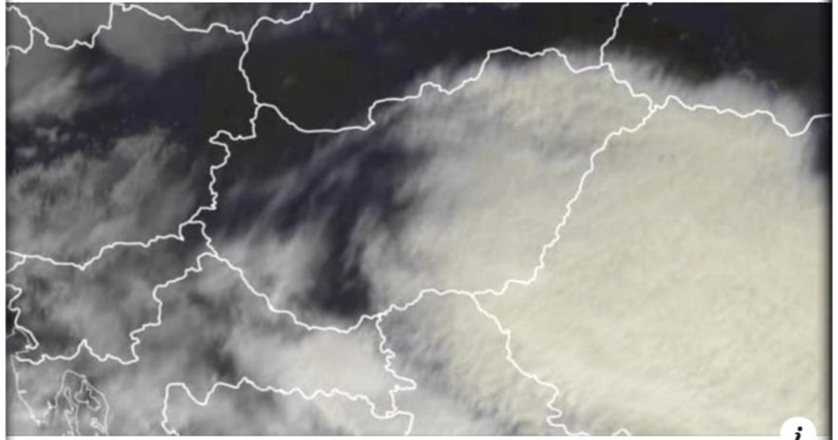
ERNYŐ ÉS POR

Tegnap megérkezett egy jókora adag szaharai por, amely szép cirrusernyőt hozott létre az ország keleti, majd középső felén is. A tőlünk délnyugatra örvénylő ciklon elődoldalán továbbra is nedves, enyhe léghullámok érkeztek, így a szokásos módon a sokéves átlagnál jóval melegebb volt. Éjszaka mindenütt megvastagodott a felhőzet, és hajnalban, reggel csapadéktevékenység is előfordult.

Ma összességében többfelé kell esőre, záporra számítani, és mivel még mindi... **See more**

Időkép
February 29 at 12:34 PM ·

Elmarad a napsütés a keleti országrészben, a szaharai por a ludas
Borítókép: Műholdfelvétel csütörtök délelőtt

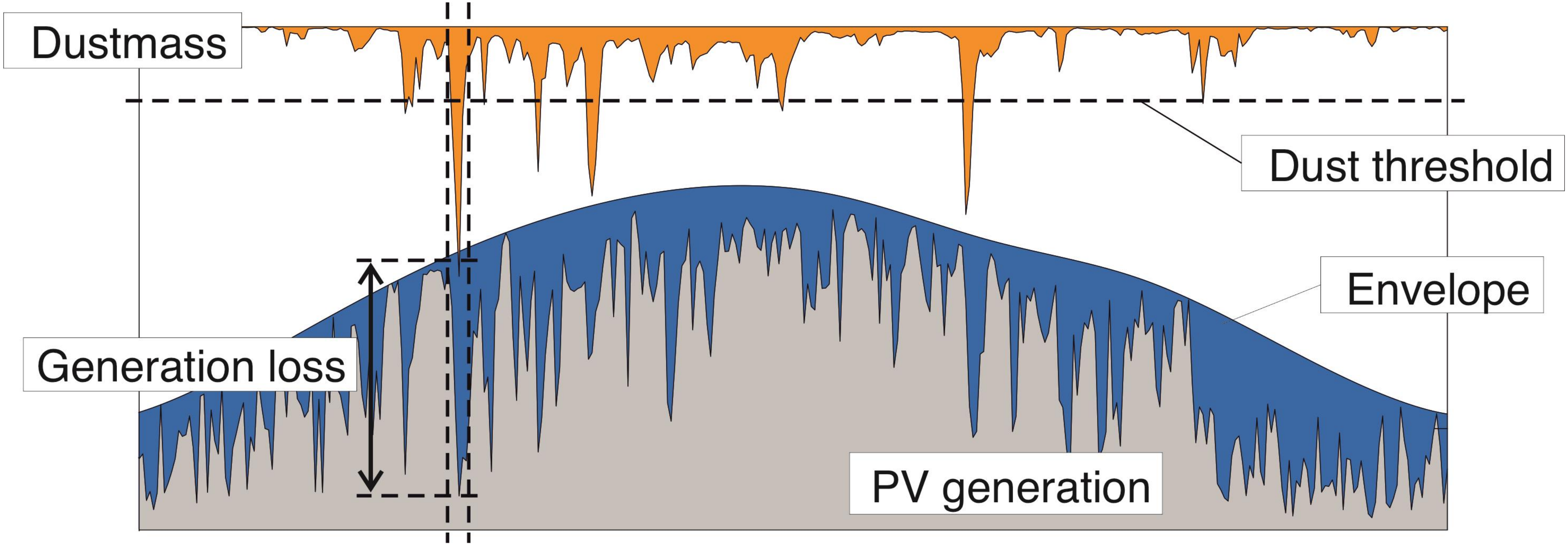


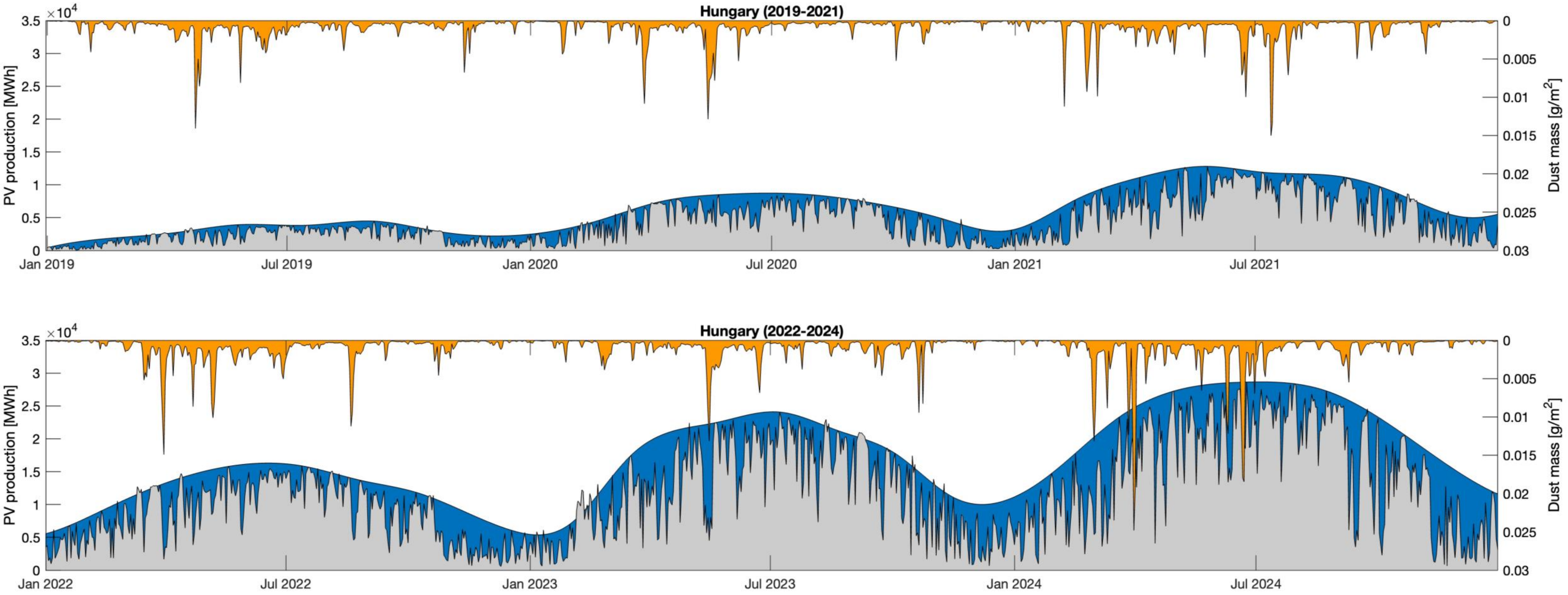
IDOKEP.HU

Hatalmas cirrusernyő gátolja a napsütést az ország keleti felén

A magasban érkezett szaharai por keltette életre a nagy területre kiterjedő fátyolfelhőzetet.

Szaharai por hatása a PV termelésre




Hungary (2019-2021)
Hungary (2022-2024)
PV production [MWh]
Dust mass [g/m2]
×10^4
3.5
3
2.5
2
1.5
1
0.5
0
0.005
0.01
0.015
0.02
0.025
0.03
Jan 2019
Jul 2019
Jan 2020
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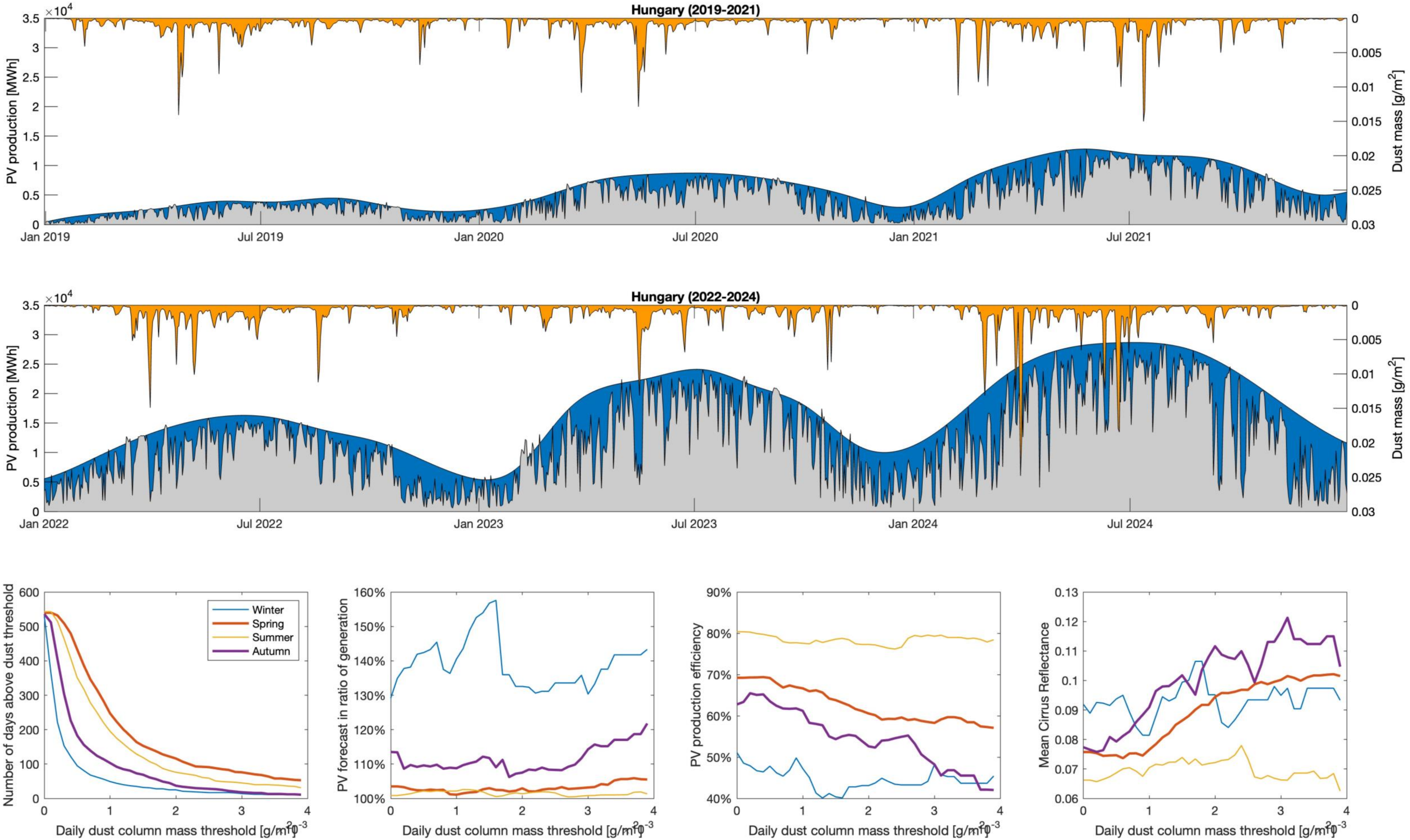
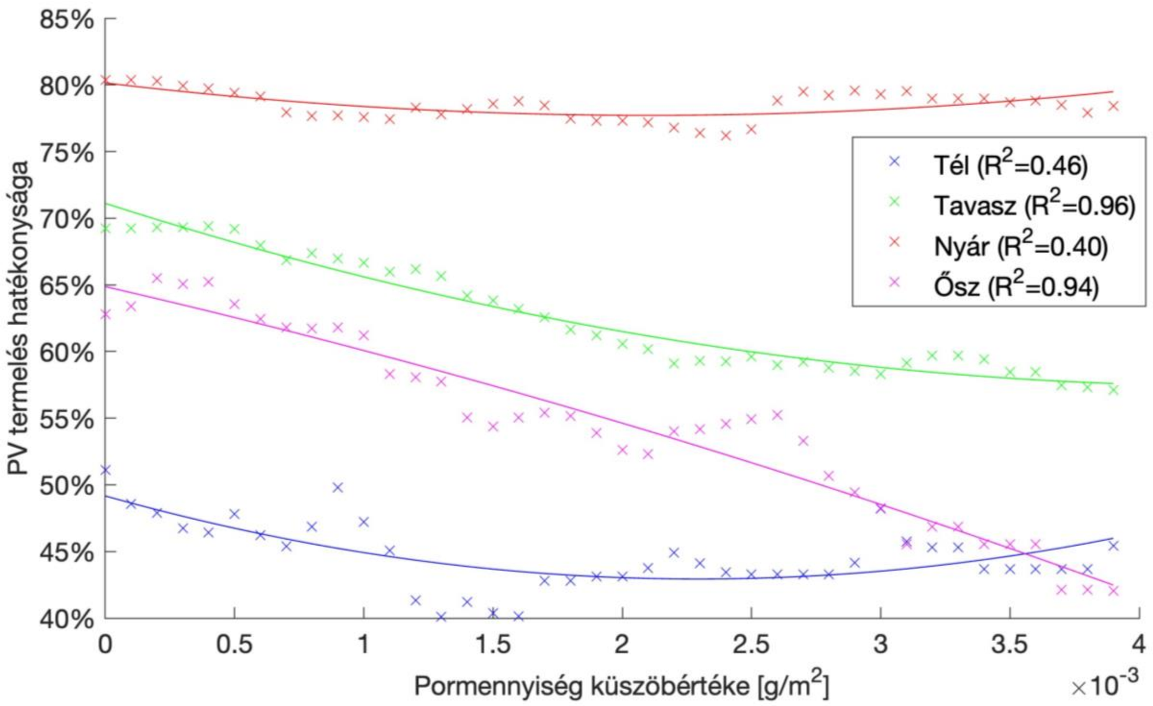
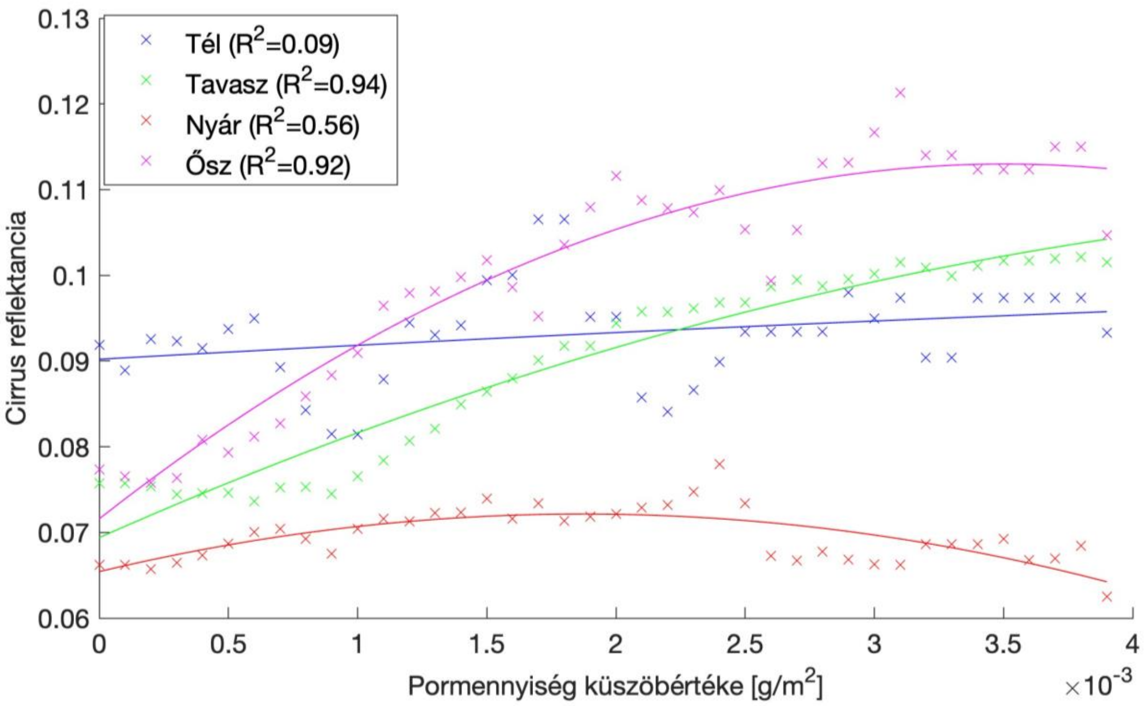
Jul 2023
Jan 2024
Jul 2024



Hungary (2019-2021)
PV production [MWh]
$\times 10^4$
Dust mass [g/m²]
Jan 2019
Jul 2019
Jan 2020
Jul 2020
Jan 2021
Jul 2021
Hungary (2022-2024)
PV production [MWh]
$\times 10^4$
Dust mass [g/m²]
Jan 2022
Jul 2022
Jan 2023
Jul 2023
Jan 2024
Jul 2024
Number of days above dust threshold
Winter
Spring
Summer
Autumn
Daily dust column mass threshold [g/m²]
10^{-3}
PV forecast in ratio of generation
Daily dust column mass threshold [g/m²]
10^{-3}
PV production efficiency
Daily dust column mass threshold [g/m²]
10^{-3}
Mean Cirrus Reflectance
Daily dust column mass threshold [g/m²]
10^{-3}

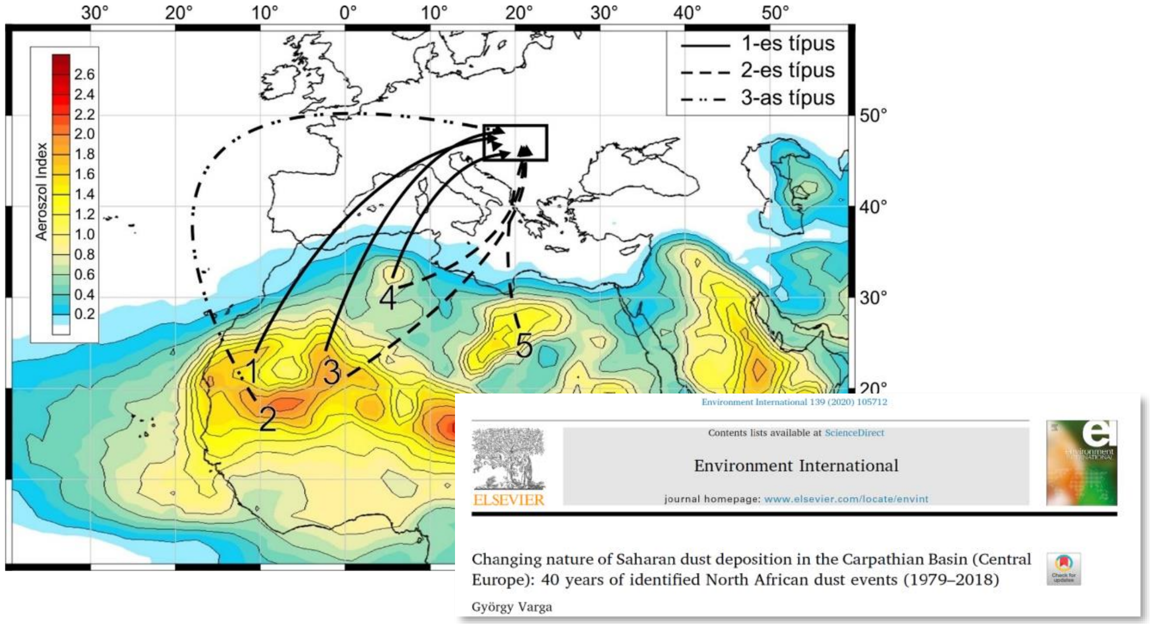
Szaharai por hatása a PV termelésre

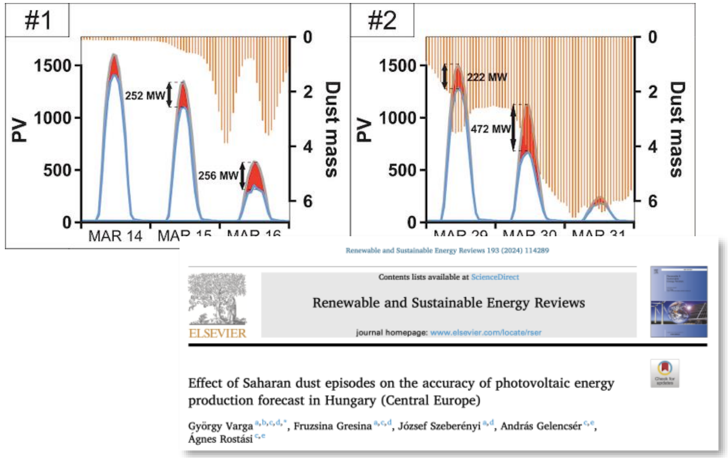




Szaharai por hatása a PV termelésre

- **Hazánkat érintő szaharai porviharos** események viszonylag gyakoriak (**n>290 45+ év alatt**)
    - gyakoriságuk és intenzitásuk **növekszik**;
    - az ország területén kiülepedett por mennyisége évente **több százezer tonnára** tehető;
    - **mennyisége a klímaváltozás következtében vélhetően nőni fog**.

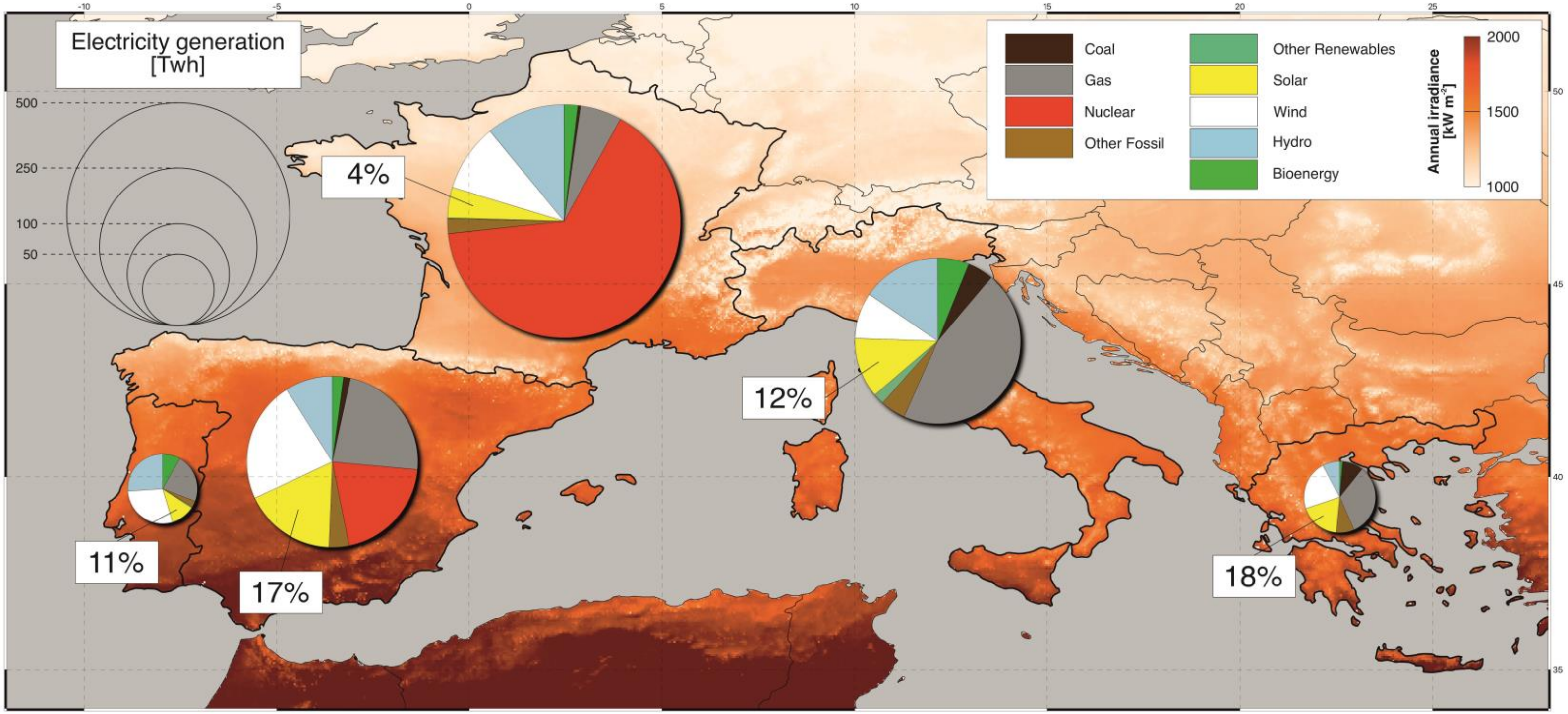


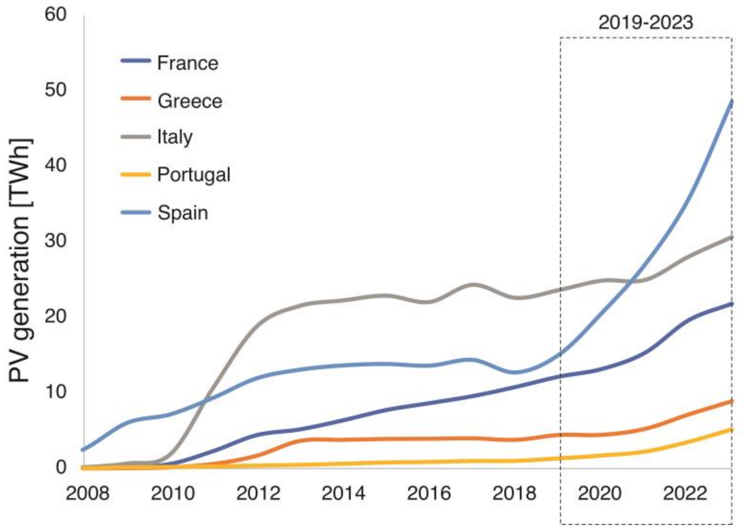


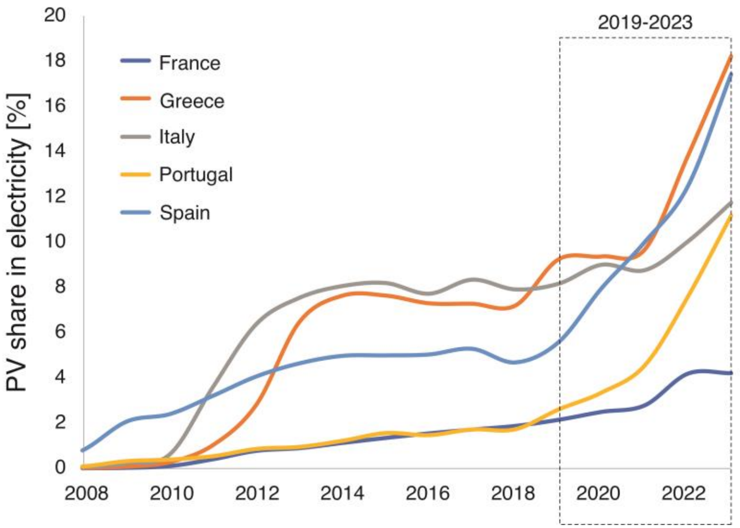
- közvetlen és közvetett (pl. felhőképződés) hatásai révén a **besugárzás mértékét csökkenti**;
- a panelek felületére kiülepedett poranyag **rontja annak hatásfokát**;

- **menetrendezés szempontjából releváns** légköri összetevő, DE:
    - a légköri por **parametrizálása** nem megfelelő a numerikus szimulációkban;
    - a számítások során **aeroszol klimatológia** (értsd sokéves átlag) adatokra hagyatkoznak
    - **felhőképződésben** betöltött szerepét nem vizsgálják

MTA Szaharai por hatása a PV termelésre: Dél-Európa







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The shadow of the wind: the impact of Saharan dust on photovoltaic power generation in the Mediterranean

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A B S T R A C T

The increasing frequency and intensity of Saharan Dust Events (SDEs) in Europe poses a significant challenge to the reliability of photovoltaic (PV) energy systems. This study examines SDE effects on solar power in five Mediterranean countries – Portugal, Spain, France, Italy, and Greece – from 2019 to 2023, using dust data, PV statistics, and meteorological analysis. The findings of this study demonstrate that SDEs reduce PV output by an average of 25–40 %, with losses exceeding 50 % during extreme events. In Portugal this decline was 10.1–29.3 %, 16.3–19.8 % in Spain; 4.4–40.5 % in France; 13.9–36.8 % in Italy and 20.1–40.9 % in Greece, during the highest dust levels. Solar irradiance drops are due to both dust-induced attenuation and increased cirrus cloud formation from enhanced ice nucleation. Analysis of recent dust storms shows consistent day-ahead PV forecast errors, with underestimations up to −15 % in Portugal and Spain, and overestimations up to +10 % in Italy and Greece, highlighting the need for improved models that incorporate aerosol-cloud interactions. The results highlight the need for improved forecasting that includes real-time dust monitoring and cloud processes. As SDEs increase with climate change, accounting for dust-related uncertainties is crucial for reliable grid operation and solar power planning in southern Europe.

1. Introduction

Renewable electricity generation is a key priority in a globalised world facing sustainability, climate and geopolitical crises. The balance between the trilemma of electricity generation: (1) security of supply, (2) affordability and (3) sustainability has become difficult to maintain. Energy sovereignty ambitions and climate protection objectives, which are fundamental to overall energy production, have shifted the national energy mix towards renewables, and in particular weather-dependent renewables.

In order to meet sustainable development goals and climate policy directives with a focus on decarbonization — alongside strong national interests in energy independence — most European countries have seen a steep increase in the share of renewables in electricity production [1]. The countries under scrutiny in this study are indisputably those with the highest potential for solar energy production, a fact attributable to their geographical location within Europe. Nevertheless, they exhibit vast differences in their historical development of PV energy utilisation, primarily for political and economic reasons. In addition, both the economic crisis of 2008 and the economic comeback after the COVID-19 pandemic impacted these countries differently and influencing their energy policies.

The global integration of PV production underscores the imperative to scrutinise all factors influencing the output of weather-dependent renewable power generation systems. It is an established fact that Saharan dust storm events (SDEs), which have become increasingly more frequent recently, attenuate solar irradiance, thus reducing the power output of photovoltaic panels [2,3]. A marked increase in the frequency and intensity of SDEs reaching the European continent has been observed in recent years, attributed to shifting atmospheric circulation patterns resulting from changing hemispheric climate. The Sahara is the largest single source of mineral dust on Earth, releases billions of tonnes of mineral dust into the atmosphere each year, which is occasionally transported over long distances. Tens of millions of tonnes of Saharan dust are transported and settle on the European continent annually [4,5]. During intensive SDEs, significant amounts of particulate matter can settle on the surface of solar panels, reducing the efficiency of PV production. In the present study, we do not aim to analyse this process, but to investigate the relationship between SDEs and irradiance. Aerosol particles in general, and mineral dust particles in

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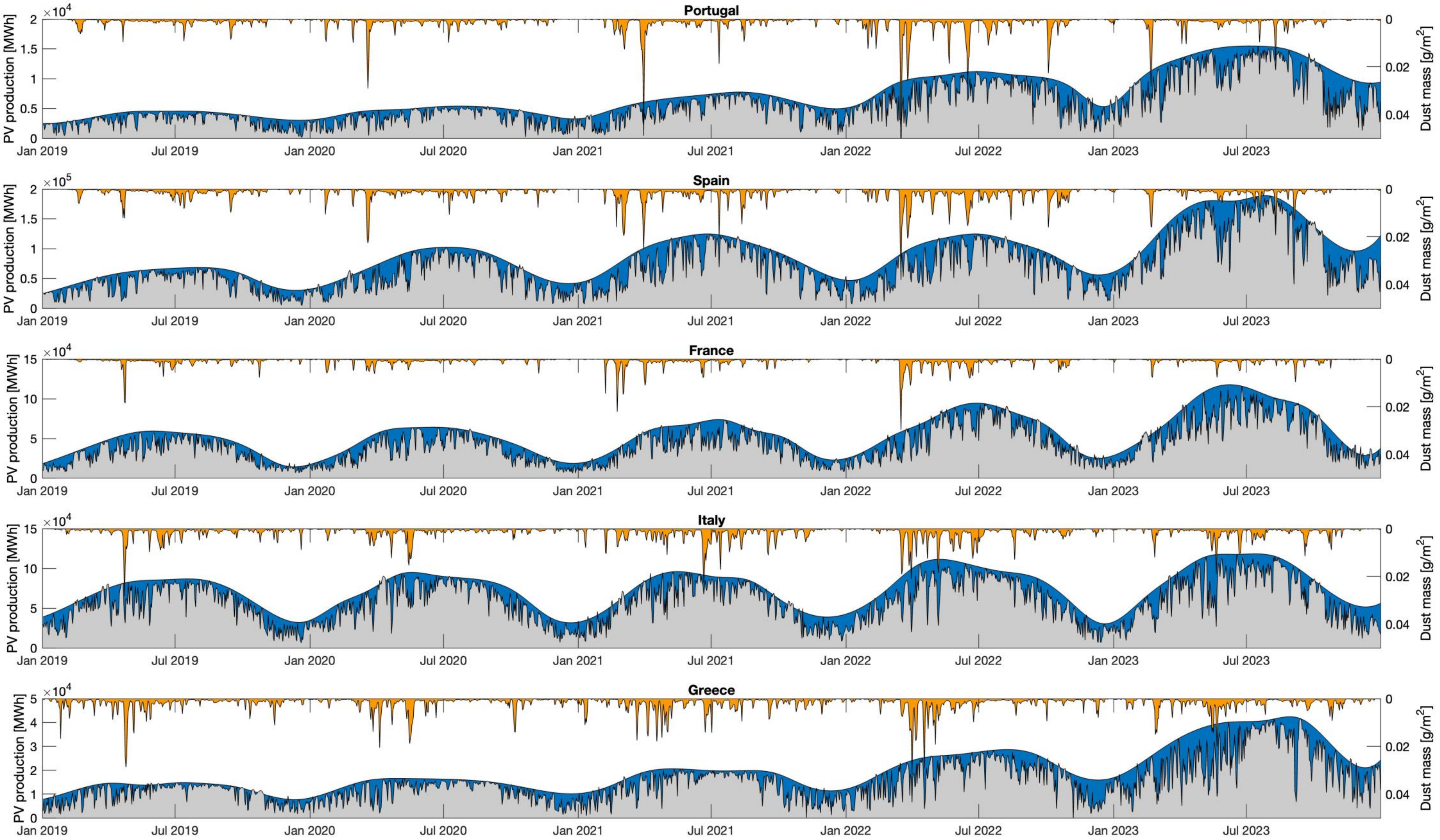
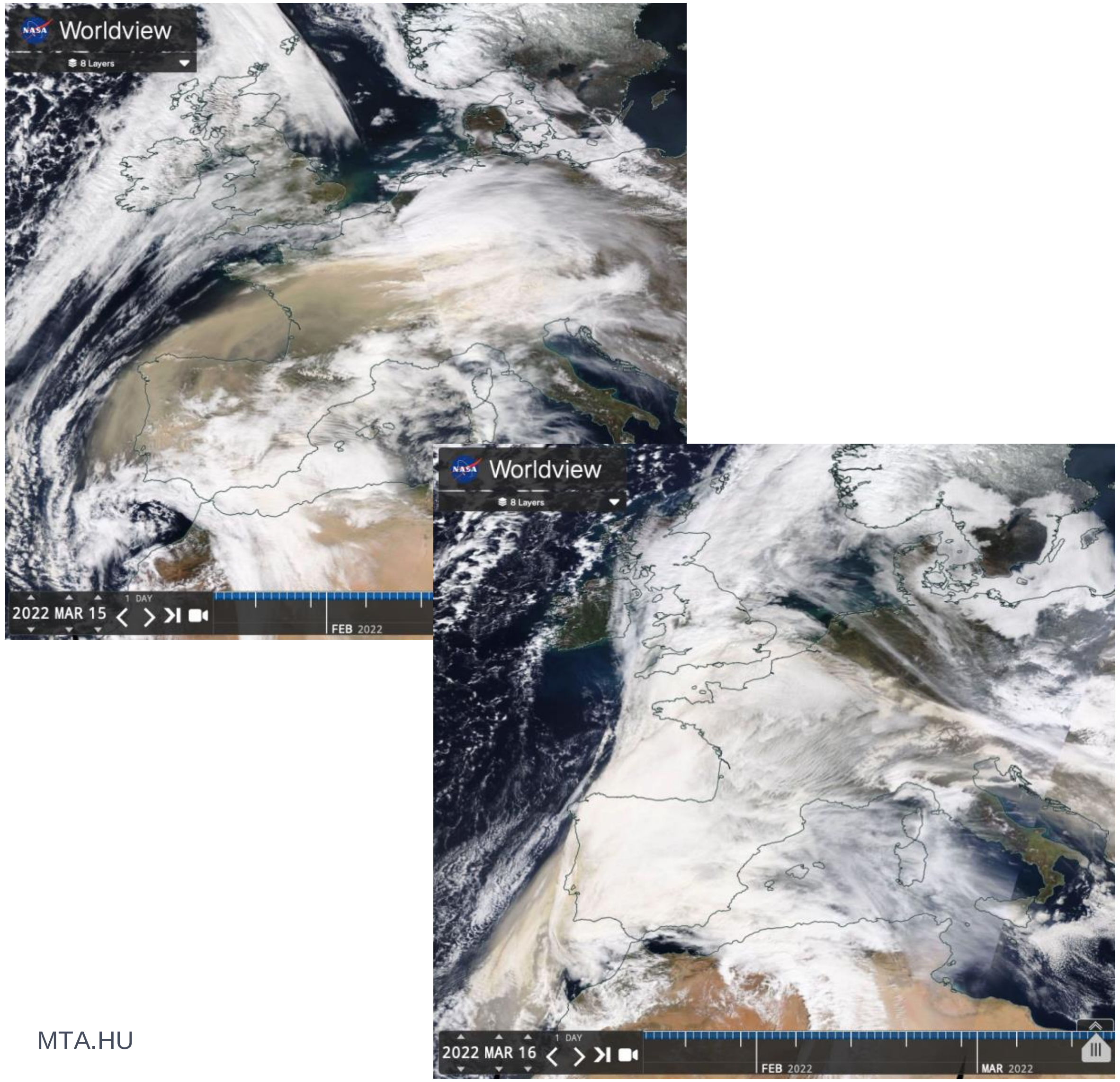
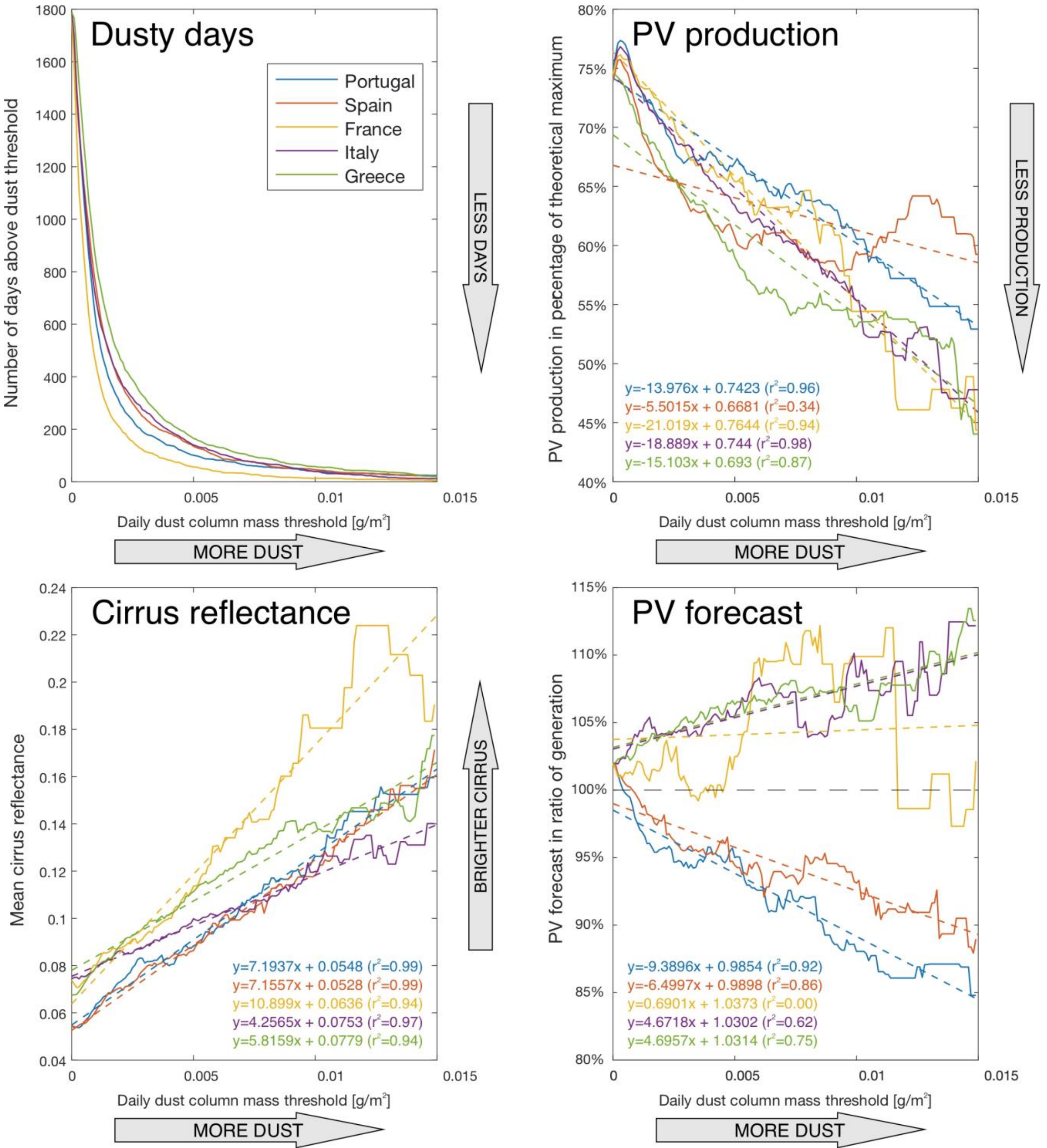
Szaharai por hatása a PV termelésre: Dél-Európa

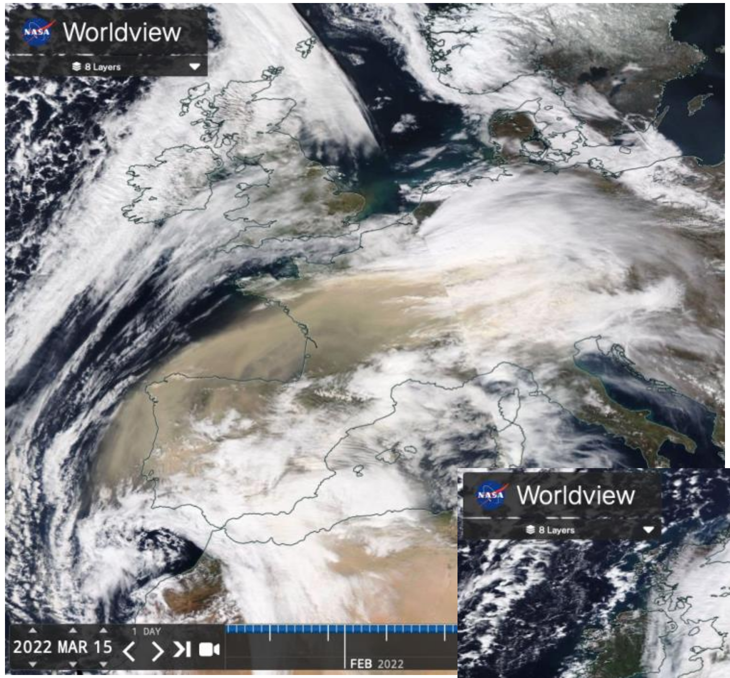


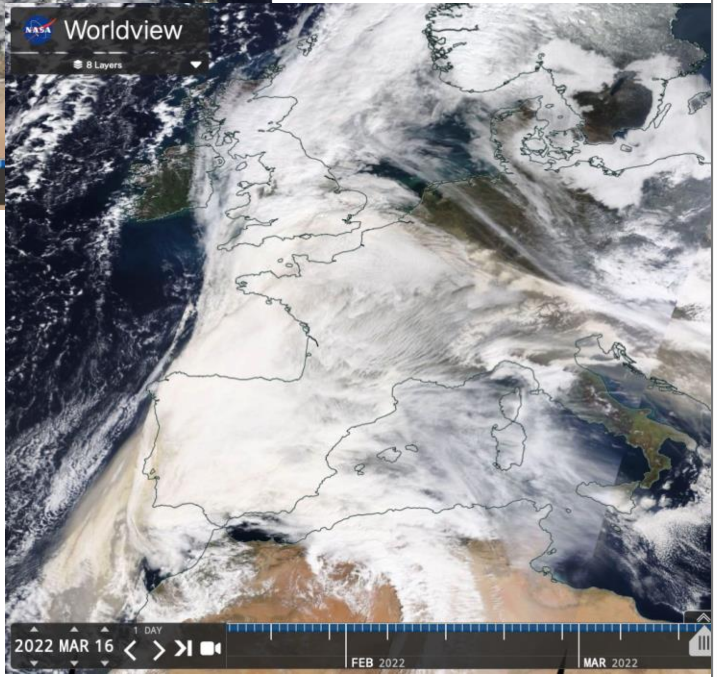
Szaharai por hatása a PV termelésre: Dél-Európa

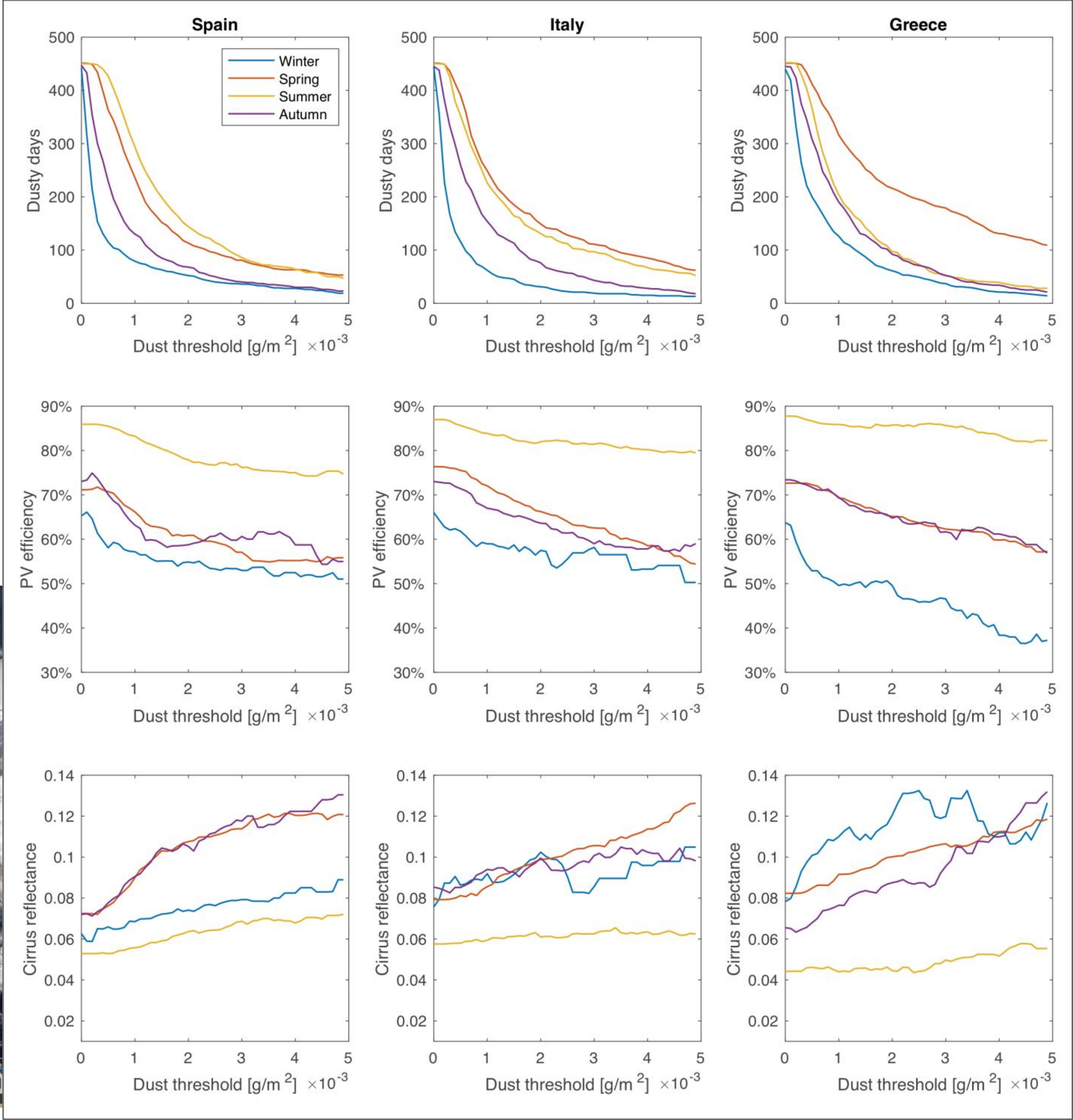


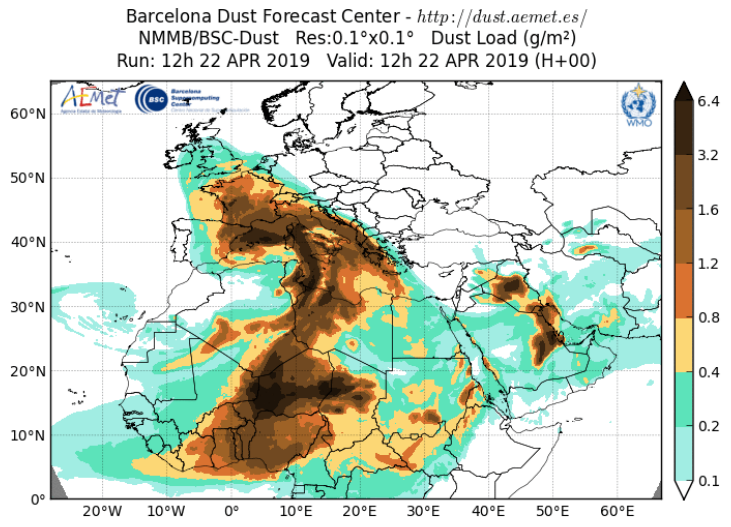


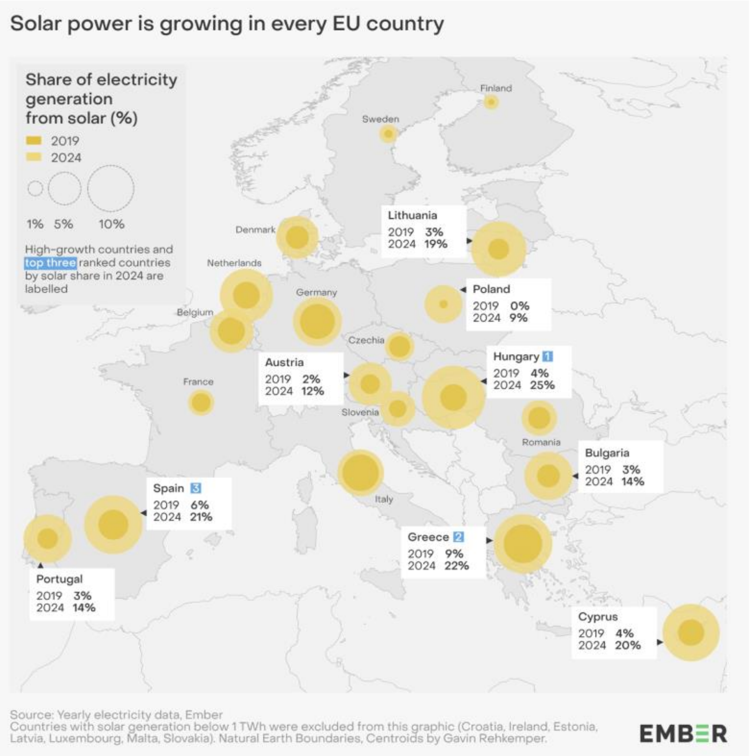
Szaharai por hatása a PV termelésre: Dél-Európa











Tanulságok

1. A **légköri por hatása jelentős**, mind a fotovoltaikus termelésre, mind a termelés előrejelzésére.

2. A PV-termelésre vonatkozó **előrejelzések nem lehetnek kellően pontosak**, ha durva felbontású aeroszol-klimatológiai adatokat használnak az aeroszol-felhő kölcsönhatások figyelembevétele nélkül.

3. A légköri por mennyisége, a transzportdinamika és a poranyag ásványtani és fizikai tulajdonságai (szemcseméret, szemcseforma) **nem ismertek kellő mértékben**.

4. Az éghajlatváltozás és az éghajlati rendszer természetes változékonysága miatt az előrejelzések egy instabil hidrometeorológiai és légköri rendszerben készülnek, ami mindig bizonytalanságokat hordoz magában. Ezek **a hibák a PV-kapacitás növekedésével egyre jelentősebbek lesznek**, így kezelésükhöz az egyre pontosabb előrejelzések mellett a villamosenergia-tárolási kapacitás bővítésére és megújuló diverzifikációra is szükség lesz.

MTA 200 ÉVES A MAGYAR TUDOMÁNYOS AKADÉMIA

Köszönöm a figyelmet!

MTA