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EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research, Development and Education

CO$_2$ Emission of Vaccine – Refrigerant Load

# Short-term Positive Impact

- **NO₂ in the EU**

<table>
<thead>
<tr>
<th>Country</th>
<th>Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spain</td>
<td>-61 %</td>
</tr>
<tr>
<td>France</td>
<td>-52 %</td>
</tr>
<tr>
<td>Italy</td>
<td>-48 %</td>
</tr>
<tr>
<td>Portugal</td>
<td>-46 %</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>-45 %</td>
</tr>
<tr>
<td>Denmark</td>
<td>-43 %</td>
</tr>
<tr>
<td>Slovenia</td>
<td>-41 %</td>
</tr>
<tr>
<td>Norway</td>
<td>-39 %</td>
</tr>
<tr>
<td>Sweden</td>
<td>-38 %</td>
</tr>
<tr>
<td>Switzerland</td>
<td>-37 %</td>
</tr>
<tr>
<td>Belgium</td>
<td>-35 %</td>
</tr>
<tr>
<td>Austria</td>
<td>-34 %</td>
</tr>
<tr>
<td>Netherlands</td>
<td>-32 %</td>
</tr>
<tr>
<td>Luxembourg</td>
<td>-31 %</td>
</tr>
<tr>
<td>Germany</td>
<td>-31 %</td>
</tr>
<tr>
<td>Poland</td>
<td>-25 %</td>
</tr>
<tr>
<td>Hungary</td>
<td>-21 %</td>
</tr>
<tr>
<td>Czechia</td>
<td>-20 %</td>
</tr>
</tbody>
</table>

Short-term Positive Impact
- $\text{PM}_{10}$ in the EU

Expected concentrations without lockdown measures

Measured concentrations with lockdown measures

<table>
<thead>
<tr>
<th>Country</th>
<th>Expected Concentration</th>
<th>Measured Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spain</td>
<td>-30 %</td>
<td>-30 %</td>
</tr>
<tr>
<td>Norway</td>
<td>-26 %</td>
<td>-26 %</td>
</tr>
<tr>
<td>Italy</td>
<td>-25 %</td>
<td>-25 %</td>
</tr>
<tr>
<td>Austria</td>
<td>-20 %</td>
<td>-20 %</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>-20 %</td>
<td>-20 %</td>
</tr>
<tr>
<td>Belgium</td>
<td>-16 %</td>
<td>-16 %</td>
</tr>
<tr>
<td>Poland</td>
<td>-16 %</td>
<td>-16 %</td>
</tr>
<tr>
<td>France</td>
<td>-16 %</td>
<td>-16 %</td>
</tr>
<tr>
<td>Slovakia</td>
<td>-15 %</td>
<td>-15 %</td>
</tr>
<tr>
<td>Germany</td>
<td>-12 %</td>
<td>-12 %</td>
</tr>
<tr>
<td>Czechia</td>
<td>-9 %</td>
<td>-9 %</td>
</tr>
</tbody>
</table>

Consumption and Resource Use

- The COVID-19 pandemic has caused significant changes in the production and consumption of plastics, and in plastic waste.
- Surge in global demand for personal protective equipment (PPE)
- Consumption of single-use plastic packaging and products
- Reduced economic activity has seen sharp falls in global oil prices. Significantly cheaper for manufacturers to produce plastic goods from virgin, fossil-based material than recycled plastic

Energy Demand – Projection (Impacted by COVID-19)

Before the pandemic, prediction in 2050 = 456 exajoules (EJ)
Now, pandemic will reduce energy demand through to 2050 by 8%, resulting in energy demand in 2050 at almost exactly the level it was in 2018.

Improvements in energy intensity will remain the most important factor in reducing energy demand in the coming decades

Impacts of COVID-19 on Global Emissions

Global emissions from economic sectors will decrease by 3.9 to 5.6% in 5 years (2020 to 2024) compared with a no-pandemic baseline scenario.

Changes in Carbon Dioxide

A positive figure in a given year indicates that emissions were higher than the previous year. A negative figure indicates they were lower than the year before.

Source: Our World in Data based on Global Carbon Project

<ourworldindata.org/co2-emissions>
CO$_2$ and Temperature Fluctuations – Geological Timescale

http://www.biocab.org/Climate_Geologic_Timescale.html
Impact of Travel Bans on CO$_2$ Emissions

<www.statista.com/study/79011/environmental-effects-of-covid-19/>
NO$_2$ across Europe (2020)

Nitrogen dioxide levels plummet across Europe
Reductions in NO2 emissions during April lockdowns in selected countries

<www.statista.com/study/79011/environmental-effects-of-covid-19/>
Industrial production in the EU increased by 0.7% in January 2021 compared with December of last year. In December industrial production had stagnated. After strong declines in March and April industrial growth had picked up in May, June, and July and remained rather stable in the subsequent months. As a result of the recent increase the total production level is now almost back (99.8%) at the level before the crisis.

Between January 2021 and January 2020 the production of computers and communication equipment increased by 25.8%. The production of wearing apparel dropped by 24.4%.

**CH₄ and N₂O Emission**

- Concentrations increased significantly throughout the 20th century, and particularly sharply in the second half.
- Coincides with the rise of the use of nitrogenous fertilizers and large increases in global food production.

- from 1900 to the year 2000, atmospheric methane doubled – from around 900 to 1800 ppb.

![Methane (CH₄) atmospheric concentration](source-image)

![Nitrous oxide (N₂O) atmospheric concentration](source-image)

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Source: European Environment Agency (EEA) & National Oceanic and Atmospheric Administration (NOAA)

<ourworldindata.org/atmospheric-concentrations>
Concentration of Carbon Dioxide

415 ppm (January 2021)

Source: climate.nasa.gov

<climate.nasa.gov/vital-signs/carbon-dioxide/>
Growth Rates (2020 vs 2021)

Global Mobility Changes Due to COVID-19

Big Data Analytics on COVID-19 Mitigation in Singapore

- Singapore has close to 1 M vehicle population;
- The 1,904 car parks are located in 31 regions in Singapore. The resident population in the 31 regions covers 99.3% of Singapore;
- More than 3 M pieces of real-time data records (e.g. name, time of records, total lots and available lots) are saved every day.

Air Emissions Changes Based on Mobility in Singapore

The comparison of the transportation-related average air emissions estimation before and during the circuit breaker under (a) the 25.0 % (Scenario 1) and (b) the 40.0 % (Scenario 2) reduction in average distance travelled.

Vaccination in Russian Federation

- 8,735,310 (5.98% of the population) – vaccinated with 1 dose
- 5,419,537 (3.71% of the population) - fully vaccinated (data for 1 region is missing)
- 14,154,847 - all vaccinations are made on average on the basis of data for the last week
- 167,380 day (0.11% of the population)
- At this rate, 50% of the population should be vaccinated in 385 days
- 280,993 units/d - the number of completed vaccinations

Can Sputnik V reverse the course of vaccination in the EU? Figures and facts, ttps://www.dw.com/ru/mozhet-li-sputn ...
Energy demand development. (a) The projected drops of energy demand by regions in the whole year of 2020, (b) The year-on-year growth rates of energy demand in 2019 and 2020 (projected).

Healthcare-energy-environment system during the COVID-19 pandemic.

The conceptual diagram of the healthcare-energy-environment nexus under climate change constraints.

The Sixth Wave of Innovation Triggers by COVID-19

Representative Work

36 news outlets, 3 institution special reports, 1 blog, and 74 tweeters have cited/reported this work.

Energy and Environmental Footprints of PPE & Disinfection

Hospital Building and Equipment utilisation → 22.2 M cases and 34 % hospitalisation = ~356 PJ

Test Kits
- Nylon-plastic Swabs
- Plastic Vials
- Chemical Reagents Bottle etc.

→ 390 M test conducted = ~168 TJ

Personal Protective Equipment
- Shield → 3.9 TJ/month
- Masks → 4.6 PJ/month
- Gloves → 7.0 TJ/month

Ethanol Production related to disinfectants

Packaging

Waste Disposal/Treatment

12.3 % growth in demand → ~181 PJ

Emergency transporting, by e.g. plane, consumes more energy where the supply chain is usually not being optimised

Diversifying Solution
- vital strategy to improve the susceptibility to unexpected events.
- provides flexibility in optimising energy consumption and environmental footprints without compromise on the effectiveness of diseases outbreak measures

Estimated Healthcare Waste

**Healthcare waste generated before the COVID-19 pandemic**

- **Manila**: 47 metric tons per day
- **Jakarta**: 35 metric tons per day
- **Kuala Lumpur**: 35 metric tons per day
- **Bangkok**: 27 metric tons per day
- **Ha Noi**: 26 metric tons per day

**Estimated healthcare waste generated during the COVID-19 pandemic**

- **Manila**: 280 metric tons per day
- **Jakarta**: 212 metric tons per day
- **Kuala Lumpur**: 210 metric tons per day
- **Bangkok**: 160 metric tons per day
- **Ha Noi**: 154 metric tons per day

Supplies of Vaccine and Ingredients: EU

1. Specialist plastic bags used inside pharmaceutical bioreactors flow back and forth between the US and the EU
2. 1m vaccine doses from the EU to the US
3. 3.1m vaccine doses from the EU to Mexico
4. 1.4m vaccine doses from the EU to Saudi Arabia
5. 5m AstraZeneca doses from India to the UK
6. Lipid nanoparticles are shipped to Pfizer's Belgian plant from the UK
7. Pfizer supplies the UK with vaccines from Belgium
8. 9.1m doses from the EU to the UK
9. Moderna makes vaccine ingredients in Switzerland, fills and finishes the vials in Spain and ships to the UK and rest of world

<www.ft.com/content/773245da-900a-468e-aaf3-96ec8c43341f>
## Specific Heat Loss during Transportation and Storage (per dosage)

<table>
<thead>
<tr>
<th>Vaccine company</th>
<th>European Union $T_{\text{amb}}=20.3^\circ \text{C}$</th>
<th>Russian Federation $T_{\text{amb}}=3.8^\circ \text{C}$</th>
<th>Singapore $T_{\text{amb}}=27.6^\circ \text{C}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pfizer</strong></td>
<td>$q_{\text{ref. dose}}$, $10^{-5}$W/h/dose</td>
<td>$q_{\text{ref. dose}}$, $10^{-5}$W/h/dose</td>
<td>$q_{\text{ref. dose}}$, $10^{-5}$W/h/dose</td>
</tr>
<tr>
<td>$T_{\text{stor}}=-70^\circ \text{C}$</td>
<td>447.9</td>
<td>366.0</td>
<td>484.1</td>
</tr>
<tr>
<td><strong>Moderna</strong></td>
<td>$q_{\text{ref. dose}}$, $10^{-5}$W/h/dose</td>
<td>$q_{\text{ref. dose}}$, $10^{-5}$W/h/dose</td>
<td>$q_{\text{ref. dose}}$, $10^{-5}$W/h/dose</td>
</tr>
<tr>
<td>$T_{\text{stor}}=-20^\circ \text{C}$</td>
<td>199.9</td>
<td>118.0</td>
<td>236.1</td>
</tr>
<tr>
<td><strong>Sinovac</strong></td>
<td>$q_{\text{ref. dose}}$, $10^{-5}$W/h/dose</td>
<td>$q_{\text{ref. dose}}$, $10^{-5}$W/h/dose</td>
<td>$q_{\text{ref. dose}}$, $10^{-5}$W/h/dose</td>
</tr>
<tr>
<td>$T_{\text{stor}}=2^\circ \text{C}$</td>
<td>90.8</td>
<td>8.9</td>
<td>127.0</td>
</tr>
<tr>
<td><strong>Sinopharm</strong></td>
<td>$q_{\text{ref. dose}}$, $10^{-5}$W/h/dose</td>
<td>$q_{\text{ref. dose}}$, $10^{-5}$W/h/dose</td>
<td>$q_{\text{ref. dose}}$, $10^{-5}$W/h/dose</td>
</tr>
<tr>
<td>$T_{\text{stor}}=2^\circ \text{C}$</td>
<td>90.8</td>
<td>8.9</td>
<td>127.0</td>
</tr>
<tr>
<td><strong>Sputnik V</strong></td>
<td>$q_{\text{ref. dose}}$, $10^{-5}$W/h/dose</td>
<td>$q_{\text{ref. dose}}$, $10^{-5}$W/h/dose</td>
<td>$q_{\text{ref. dose}}$, $10^{-5}$W/h/dose</td>
</tr>
<tr>
<td>$T_{\text{stor}}=-18^\circ \text{C}$</td>
<td>190.0</td>
<td>108.1</td>
<td>226.2</td>
</tr>
</tbody>
</table>

Estimated by the authors based on several information and equation collected from the literature.
Specific Electrical Power Used to Maintain the Temperature (per dosage)

<table>
<thead>
<tr>
<th>Vaccine Company</th>
<th>European Union</th>
<th>Russian Federation</th>
<th>Singapore</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>COP</td>
<td>$W_{el.dose}$, $10^{-5}$W/h/dose</td>
<td>COP</td>
</tr>
<tr>
<td>Pfizer</td>
<td>0.7</td>
<td>639.8</td>
<td>0.7</td>
</tr>
<tr>
<td>Moderna</td>
<td>2.1</td>
<td>95.2</td>
<td>2.1</td>
</tr>
<tr>
<td>Sinovac</td>
<td>3.7</td>
<td>24.5</td>
<td>3.7</td>
</tr>
<tr>
<td>Sinopharm</td>
<td>3.7</td>
<td>24.5</td>
<td>3.7</td>
</tr>
<tr>
<td>Sputnik V</td>
<td>2.2</td>
<td>86.3</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Estimated by the authors based on several information and equation collected from the literature.
Air Cargo

Air cargo capacity is still down significantly with no rebound expected in time for vaccine distribution.

![Graph showing capacity and gap between regions for air cargo]

**Capacity, international ACTK, % growth year-over-year**
- Dedicated freighters
- Belly cargo

**Gap between regions, international ACTK, % year-over-year**
- Globally: -28
- Europe: -33
- Latin America: -33
- Asia-Pacific: -32
- Africa: -25
- Middle East: -24
- North America: -20

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1. Available cargo tonnes-kilometers.
2. Forecast based on industry experts.

Source: Air Cargo Analysis, Clive; IHS Markit; International Air Transport Association; Oxford Economics; Seabury Consulting; World Trade Service data; McKinsey COVID-19 Trade Flow Recovery Model; McKinsey Global Institute

# Vaccine Life Cycle

## Material Extraction and Production
- **Reagents**
- **Chemical**
- **Membrane, Plastics, Vials, syringes etc**
- **Critical raw materials** (polymerases, vaccinia capping enzyme etc)

## Vaccine Production and Manufacturing
- **Synthesis, purification, design, uptake, formulation** (Bioreactor/incubator, autoclave, centrifugal, cryogenic electron microscopy)
- **Bioreactor, stirred reactors, diafilter**

## Application
- Ultra-low temperature freezers
- Thermal shippers with dry ice
- Refrigeration units
- Solar direct drive refrigerators/freezers

## Storage
- ~0.31 L fuel consumption for truck/km
- 11.95 L fuel consumption of cargo plane/km
- ~5 L fuel consumption for cooling unit/h

## End of Life Cycle Management
- Incineration, sterilization, chemical disinfection, crushing, microwave, encapsulation etc

## Energy and Materials
- ~230,734 kWh/y of power and ~ 10 Mt/y of steam
- 69,019 g vaccine/y; Required dose = ~0.1 µg saRNA, ~100 µg of mRNA
- ~ 10 – 400 W/h of refrigerator usage or ~ 0.4 kWh/kg of dry ice; 0.14 kg CO₂eq/kg dry ice and ~0.007 kg CO₂eq/ L load volume of insulating packaging
- Potential recovered pyrolytic oil = average gross calorific value of ~40 MJ/kg (Plastic Medical Waste for vaccination)

*<By the authors – under preparation>*
Cotton vs Surgical Masks

24th Conference Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction

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2nd Largest city of CZ
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Villa Tugendhat
Moravian Karst
City View
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Medlánky

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http://registration.sdewes.org/pres21
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**Golden Access**

**Impact Factor (2019)** = 2.702
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24th Conference on Process Integration for Energy Saving and Pollution Reduction - PRES'21

31 October – 3 November 2021
Brno, Czech Republic,
HYBRID-CONFERENCE (FACE2FACE + ON-LINE)

Registration is still possible!!

<https://conferencepres.site/pres21/>

The 5th Sustainable Process Integration Laboratory Scientific Conference SPIL’21

4 – 5 November 2021
Brno, Czech Republic,
HYBRID-CONFERENCE (FACE2FACE + ON-LINE)

Coming soon

<https://conferencespil.com/spil2021/>
Acknowledgements

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