A health-energy nexus perspective for Virtual Power Plants: power systems resiliency and pandemic uncertainty challenges

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Abstract. This chapter introduces and discusses a novel "health-energy nexus under pandemic uncertainty" concept, that arises as a consequence of the current pandemic that we are experiencing worldwide. In light of the pandemic implications on the power and energy systems, we discuss how the global health conditions are tightly connected with the energy consumption needs and how the two areas closely interact with each other. A real-world dataset from the Estonian energy consumption over three years (2018, 2019, 2020), together with information gathered in the recent literature, will be illustrated to motivate the foundations behind the health-energy nexus concept. Opportunities and challenges that lie behind the interaction between health and energy will be outlined, and ways to address the changes in the power systems resiliency due to pandemic conditions will be discussed. Virtual Power Plants will be presented, as a way to address the pandemic challenges and improve the systems' resiliency and reliability. A novel concept of Cyber-Physical Health-Energy Systems will be discussed. Moreover, the value of interdisciplinary education and research, together with the novel interdisciplinary domain of Energy Informatics, will be proposed as key pathways to overcoming the challenges posed by the novel health-energy nexus under pandemic uncertainty.

Keywords: virtual power plants, COVID-19, energy informatics, optimization.

1 Introduction

The recent COVID-19 pandemic outbreak has significantly changed how society functions at various levels. For power and energy systems, both the commercial and the residential load demand are experiencing a dramatic change in the pattern of consumption. The load demand, both heating and electric, used to be distributed with peak demand at the office buildings during the day, and residential demand peaks during the early morning and late afternoon/evening. Due to the "work-from-home" requirements during the pandemic, the electric demand has been flattened. Most people live indoors, even for working hours therefore the overall consumption stays flat. The office buildings normally have a higher volume of energy consumption due to their bigger size. These types of commercial demands are no longer relevant as they were before. The other sector which experienced a high degree of disruption is the transportation sector. The energy consumption in the transportation sector came to a stand-still. The energy production sector has also experienced a significant change in the utilization of the total capacity. The energy production from behind the meter generation units, such as small PV or battery banks, is mostly consumed locally instead of through grid injection. The large generation units are not fully utilized, since the total volume of consumption is reduced, due to a smaller consumption from office buildings and transportation.

The authors in [1] present the impact of COVID-19 within the power and energy sector. The climatic conditions have improved dramatically with the reduction in the NO2 and CO2 levels during the lock-down periods. The paper also outlines how the total volume of electric demand has decreased in this pandemic period, compared to previous years. Moreover, a report developed by the International Energy Agency outlines that the renewable energy generation in Europe was higher than that of fossil-fuel-based generation during the lockdown [2]. However, in the USA, the balance is gradually shifting towards higher fossil-fuel utilization. In Europe, the same trend was observed – as the total electricity demand falls, the share of renewable energy in the total generation mix increases, while the share from non-renewable resources falls. Since the overall electric demand has fallen in volume, a higher portion is met by renewable-based resources in comparison to fossil fuel-based. Indeed, new record generation from solar and PV resources is registered during the lockdown in Europe. At the same time, natural gas generation has increased due to low prices and high carbon prices.

1.1 Objectives and key contributions

The objective of this work is to introduce and discuss a novel “health-energy nexus under pandemic uncertainty” concept, that arises as a consequence of the current pandemic that we are experiencing worldwide. Traditionally, the concept of "health-energy nexus" in literature has been utilized merely to investigate the energy consumption within the healthcare system [3]. While other studies proposed a health-energy nexus concept to investigate the effect of climate change on the overall state of health of the population and accounting for the health impacts from electricity generation to justify the decarbonization needs [4]. The key contribution of this work is to propose a novel health-energy nexus perspective, that widens the scope: in light of the pandemic implications on the power and energy systems, we discuss how the global health conditions are tightly connected with the energy consumption needs and how the two areas closely interact with each other. Real-world dataset [5–8] from the Estonian energy consumption over three years (2018, 2019, 2020), together with information gathered in the recent literature, will be illustrated to motivate the foundations behind the health-energy nexus concept. Opportunities and challenges that lie behind the interaction between health and energy will be outlined, and ways to address the changes in the power systems resiliency due to pandemic conditions will be discussed. Virtual Power Plants will be presented, as a way to address the pandemic challenges and improve the systems’ resiliency. A novel concept of Cyber-Physical

Health-Energy Systems will be discussed. Moreover, the value of interdisciplinary education and research, together with the novel interdisciplinary domain of Energy Informatics, will be proposed as key pathways to overcoming the challenges posed by the novel health-energy nexus under pandemic uncertainty. Finally, the role of energy policies within the nexus will be outlined.

2 The novel “health-energy nexus, under pandemic uncertainty”

As outlined in the previous section, the recent pandemic outbreak of COVID-19 is adding new challenges and it is already affecting the energy and power sector as a whole. Therefore, new solutions should be able to address the effects of extraordinary scenarios, like the one we are currently experiencing with the COVID-19 pandemic. Utilities are looking at the impact of lessening the demand for power from commercial and industrial enterprises, and the possible rise in consumption from the residential sector, with schools and businesses closed and people ordered to work from home [9]. The pandemic outbreak opens the doors to “a new health-energy nexus”, showing that health and energy are linked to one another, and events in one particular area, can have effects on the other area. Due to the shifting of energy demand from commercial areas towards residential areas, pandemics like the current COVID-19 can lead to an outage, and thereby they represent a reliability and resiliency concern for power systems. Indeed, during the outbreak, the power network resiliency is threatened, and power companies should know which areas of the network need more attention, and which ones least.

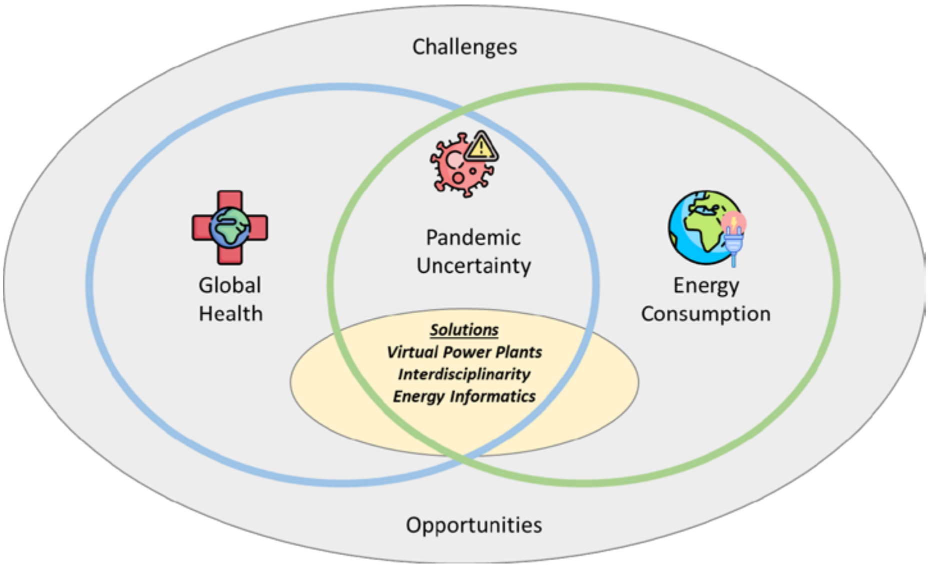

Figure 1: Key concepts of the novel health-energy nexus.

Figure 1 summarizes the key concepts of the proposed novel health-energy nexus.

The health and energy sectors are tightly interconnected, as is shown by the blue circle of health that intersects the green circle of energy. The pandemic uncertainty is the issue that lies at the intersection between health and energy. Indeed, global energy consumption has radically changed due to the pandemic situation that introduced new working and living habits for people. Thus, a health energy nexus arises, that poses both challenges and opportunities to be addressed. The main challenge is that the power and energy systems must adapt to the new energy needs that arise as a consequence of the pandemic, with particular regard to new demand curves, new demand peaks, and new demand concentrations.

The figure shows that it is possible to focus on three main concepts to address the health energy nexus challenges posed by the pandemic situation: VPP, interdisciplinarity, and the novel domain of energy informatics.

These concepts represent the main opportunities that we discuss in this work. Indeed, they are the three paths that jointly can lead to solutions to the challenges of the health energy nexus.

3 Energy demand patterns and other pandemic implications

Figure 2 shows a schematic representation of the cascaded implications of a pandemic, from societal work/life habits' change towards new energy consumption trends, that generate new emerging technical issues for power systems, leading to the need for new approaches and solutions. This is the key path that lies behind the health-energy nexus proposed and discussed in this chapter.

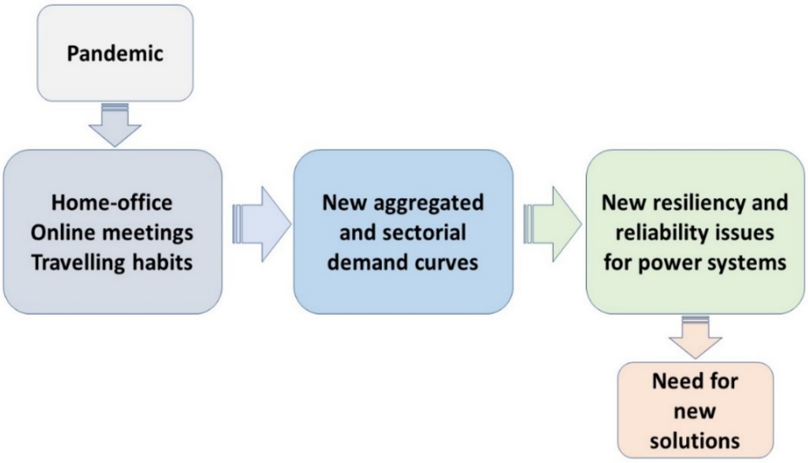

Figure 2: Cascaded implications of a pandemic: from health to energy.

As shown in the Figure, the overall pandemic situation has three main implications, which are all tightly linked to the energy and power systems field: new working habits due to home-office, higher use of online meetings due to social distancing requirements, and different traveling habits due to the overall safety restrictions.

The new advent of home-office (namely, smart-working, or home-working) generates new demand peaks and new demand concentrations, due to the shift of workers from industrial and commercial areas to residential areas. This means that it is not only the aggregated energy demand of a country that is affected by a pandemic, but it is also the sectorial energy demand that is subject to variations [10].

Another reason why the energy demand patterns change under pandemic conditions is due to the energy demand being more scattered during the day. Indeed, while before the demand was concentrated in industrial/commercial areas where offices and working places were accessible, now it is scattered in wider residential areas due to home-working requirements [11,12]. In sum, commercial and industrial demands decline, but residential demand increases [1].

Few works in the literature have recently investigated the impacts of stay-home living patterns on the energy consumption of residential buildings. The study in [13] shows that in the US, the overall electricity demand is lower because the lockdown impacts negatively the activities within commercial buildings and manufacturing sectors. However, the energy consumption for the housing sector increased by 30% during the full 2020 lockdown period. This is because of the higher occupancy patterns during daytime hours, which led to higher use of energy-intensive systems such as heating, air conditioning, lighting, and appliances.

Limited analyses have so far been conducted to evaluate the impact of lockdown and stay-at-home orders on energy use for various sectors. The study in [13] discusses sectorial demand variations pre and post COVID-19. The data gathered among Argentina, Australia, United Kingdom, Ireland, and Texas suggest that the overall trend is an increase in the residential energy demand and a decrease in the commercial and industrial energy demand. The available data are not enough to make a thorough comparison between the demand patterns in the commercial and industrial sectors.

Authors in [14] discuss the different energy consumption of industrial and commercial areas with commuting, compared to a home office. They show that consumption is interrelated, where the decrease in energy consumption in offices will lead to an increase in energy consumption at home. However, an important observation of this study, is also that the degree of increment and decrement, which contribute to the net consumption is not equivalently shifting between the options. So far there are not yet enough studies to fully understand such energy demand trends under pandemics.

In addition to the few data available in the literature, new data for the Estonian case will be presented and discussed below, to better understand the pandemic implications on the overall power system.

In Figure 3 the total electricity demand in Estonia during the years 2018-2020 is presented. In Figure 4 annual electricity consumption and the cumulative number of COVID-19 cases officially registered are presented.

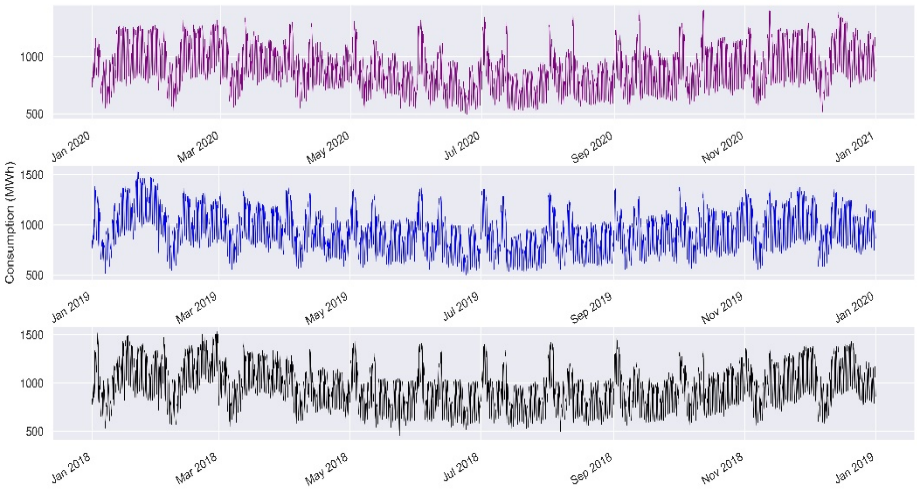

Figure 3: Total electricity consumption with hourly resolution from 2018-2020 in Estonia.

Figure 4: Number of covid cases and energy consumption in 2020 in Estonia.

The time-series data are obtained from the Estonian transmission system operator Elering [5]. Time series data describes the pattern and trends in a dataset. While electricity demand is highly correlated to the weather but also dependent on various other variables such as holidays, appliances, etc.

Three consecutive years are compared to validate if a trend is temporary or persistent. From the observations, the total volume of consumption has dropped below 1400 MWh in 2020. In the past two years, the consumption volume peaked at 1500 MWh. This validates the fact that total volume has dropped. The factor that could describe this change is the pandemic outbreak.

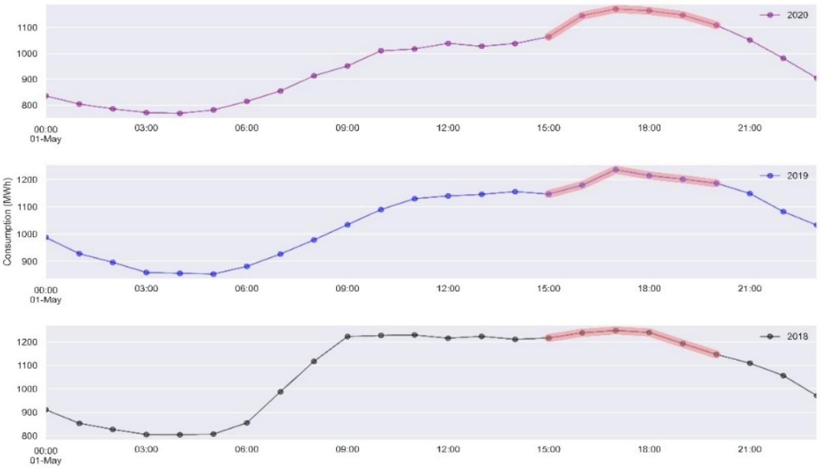

Figure 5: Electricity consumption with an hourly resolution during a day.

On 13 March 2020, the Estonian government has declared a state of emergency until 1 May which was later extended until 17 May. Looking more closely at the daily consumption patterns on 1 May over the three years, in Figure 5, it is evident that the trend has changed. Apart from the volumetric change, the trend has smoothened during the pandemic. The peak demand hours from 15:00 to 20:00 are highlighted where the trend can be observed.

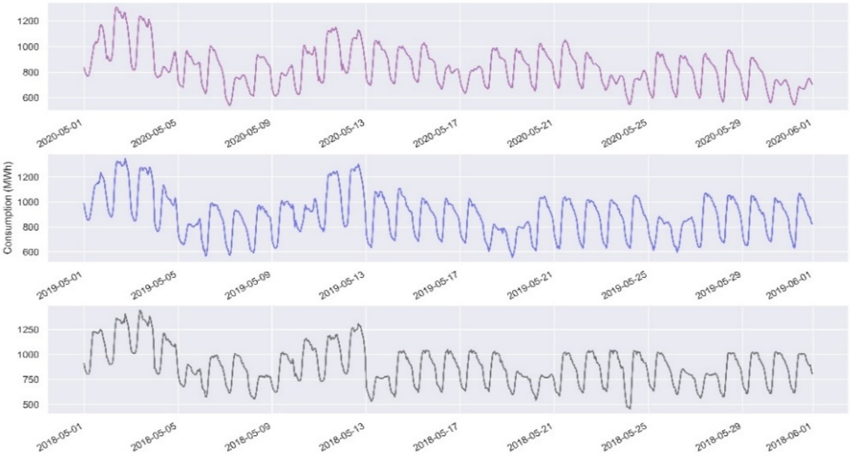

Figure 6: Electricity consumption with an hourly resolution during a month.

Moving to monthly demand patterns during May over the three years presented in Figure 6 there is a consistent change in patterns. For example, during 12, 17, and 25 May the patterns are similar during the years 2018 and 2019 while in 2020 it is different. The patterns were also observed during the first week of May as in Figure 7. During days 4 and 5.

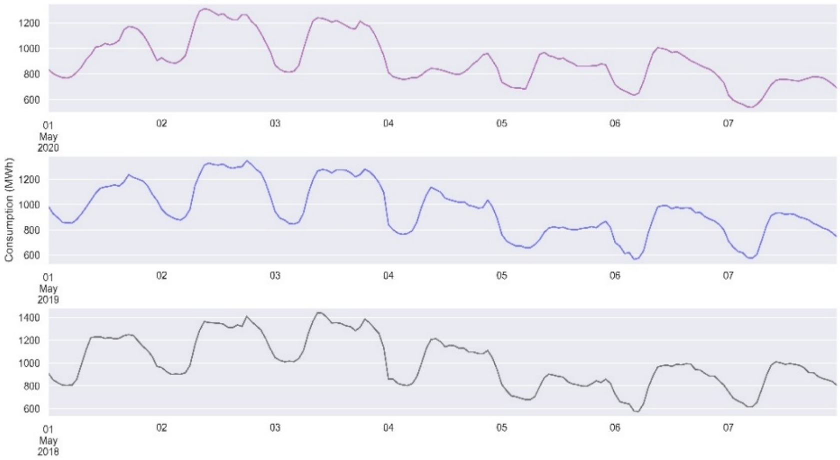

Figure 7: Electricity consumption with an hourly resolution during a week.

Histograms of the consumption are presented in Figure 8 which demonstrates the overall pattern of the consumption by how frequently certain volumes of consumption were attained. In 2020, the peak demand was 800 MWh which occurred a little over 500 times. In 2019 and 2018 the peak demand was 1000 MWh which occurred 480 times. Through this investigation, it is established that the total volume of consumption was reduced, and the pattern of consumption was changed.

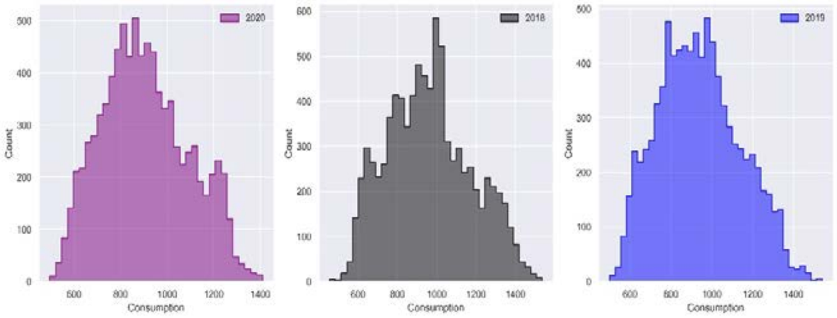

Figure 8: Distribution of electric consumption.

A similar trend was observed almost everywhere as reported by the IEA [2]. The plausible explanation is the pandemic that has impacted the way energy is consumed. Work from home has led to less energy consumption in office buildings and public places. Beyond that, the transportation sector has been significantly impacted by local and international commutes.

From a power system perspective, the power network is unevenly loaded. While normally the network has a high capacity made available to the office buildings or public places, the concentration of demand has now shifted to purely residential areas. Certain transformers are now always loaded due to the consistent demand. This has adverse effects on the life cycle of the power apparatus and might lead to voltage imbalances, brownouts, or even blackouts. The demand side flexibility has become even more important given that network replacement is a very expensive choice for system operators specifically at a distribution level.

As outlined at the beginning of this section in Figure 2, another implication of a pandemic is the higher use of data, due to heavy use of online meetings and online resources to support the home-working and social distancing requirements. The need for information and communications technologies to support digitalization has a direct impact on the energy consumption of data centers that increases heavily [14].

Finally, there are significant consequences observed in the transportation sector. From the road to rail, air and maritime transportation have experienced a fall in volume. Electric transportation through cars, buses or rail not only consumes but also stores energy to be discharged at a later stage. The consequence is that traditional fossil energy demand declines, but renewable energy demand increases [2].

The new demand patterns discussed above, create new challenges for the energy and power systems, regarding resiliency and reliability. Even though the total consumption decreases, the geographical consumption is still a problem because the distribution lines for residential consumption are overloaded, while the industrial and commercial buildings with a higher capacity of connections are underused. The pandemic implications outlined in the previous paragraphs generate a novel health-energy nexus that requires the development of new solutions, able to tackle the resulting challenges on the energy and power systems. The following sections will address three pathways to tackle the health-energy nexus, VPP, the need for interdisciplinary research, and Energy Informatics as a key domain.

4 Value of Virtual Power Plants within the novel health-energy nexus

The pandemic has shifted the focus to localized energy consumption and regeneration. Consequently, the demand side participation to provide flexibility represents a great opportunity to balance the supply with demand. A Virtual Power Plant (VPP) is formed through a collection of generation units from various sizes which are geographically dispersed. It also includes demand-side flexibility in the portfolio. One of the key challenges is optimal utilization of the non-dispatchable and renewable power generation units. A VPP can facilitate access to renewable generation units often in remote locations. This in turn will result in better utilization of the resources. Furthermore, the grid resiliency can be fostered through many small-scale units acting interim a VPP. Now that the residential consumption is peaking during the pandemic, a VPP can provide active participation for demand-side flexibility. In [15] the authors report that there is a sharp decrease in the electricity from renewable resources during the pandemic Furthermore, the investment projects for new generation units have been suspended due to a sharp fall in the electricity price. Alongside the challenges for the distribution system operator have increased due to voltage imbalance, accurate demand projections, and flexibility reserve.

As outlined in the previous section, energy consumption has changed both in volume and pattern due to the pandemic. While health concerns have triggered government policies which resulted in the change, a VPP can aid in maintaining the balance while creating economic opportunities. Demand response could provide an immediate solution to the network capacity problem. Price signals are considered as among the clear motivators for demand shifting. Coordinating each price signal to reach a certain volume of consumption is rather complex. Then predicting the consumption for the next day or week might be a too short time to draw attention. A VPP formed locally with a district or region could commit to a sizable volume of energy consumption while relaxing the coordination challenge. Then again, prosumers or small-scale producers participating within a VPP might provide flexibility both in terms of production and consumption sides.

Consequently, VPP can also reinforce the network resiliency and security by balancing the consumption and production locally to the requirements of the overall power grid. For example, the voltage imbalance due to excessive PV injection can be avoided by negative price signals [16]. In addition, the reactive power consumption or production can be shifted with a better price offer. A local energy market through a VPP can aid in maintaining overall grid resiliency and thereby enhance reliability.

Islands, suburban, rural, and other remote corners of the grid often act either as energy injection through PV or wind resources or demand. Through VPP these points can take an active role in the overall grid resiliency. During pandemic or other disaster management scenarios, they can take a more active role in balancing the overall grid. For example, if a certain plant experiences an operational failure in one of the networks, a VPP which has geographically distributed resources can provide alternative solutions how to balance the grid. Peer-to-peer interactive energy transactions [17] is gaining pace recently with energy tokenization and consumer participation. A VPP can act as a local trading platform aggregating a small region that might be geographically distributed. Through many VPPs within and across distribution system operators, the market competition would derive better value for the end-user. Unlocking economic potential and enabling participation are among the key outcomes of transactive energy which could be realized through a VPP. Aggregating the individual consumption and production potential to a certain volume would enable trading and ease of control. This phenomenon was also observed in the transportation sector through companies like Uber, Bolt, and Ola. However, any free market would require regulation and policies to avoid coalitions and motivate competition. Gradually the share of renewable resources is growing both in volume and type making the generation distributed across the geographic region. System operators would continue to own networks when the VPP can provide a local trading platform for peer-to-peer energy transactions while reinforcing the network operations.

The uncertainty arising from renewable resources and catastrophic situations such as the pandemic can also be addressed at different levels - neighborhood, city, regional levels. A VPP can facilitate uncertainty handling through various scenarios within and beyond.

Finally, a VPP platform can enable geographic expansion and flexibility pool to the power system. Scheduling the energy discharge to peak hours matching the variable energy production from renewable resources can be facilitated through a VPP. The same balancing effect can also be coordinated in air travels to different locations through scheduling flights through a VPP. Consequently, the dependence on fossil fuels could be further reduced while increasing the share of renewables in the overall energy system.

5 Energy Informatics and interdisciplinarity to tackle the novel health-energy nexus

The novel health energy nexus is an interdisciplinary concept in itself since it touches upon the two main disciplines of health and energy. However, such a concept requires an even wider interdisciplinary approach since the topics of health and energy are nowadays tightly connected to many areas of computer science. Energy Informatics, in particular, is a novel domain that lies at the intersection of energy systems, power systems, economics, computer engineering, and computer science. As such, Energy Informatics represents a valuable subject to study and address the resiliency and reliability challenges that arise within the power systems. An Energy Informatics perspective is therefore needed to tackle the novel health-energy nexus under pandemic uncertainty as well as implement VPP solutions for it. Interdisciplinarity, together with energy informatics, is therefore proposed in this section as the key instrument to address the challenges of the health-energy nexus in general and enhance the role of VPP in particular.

The key subjects of Energy Informatics have been identified in [18]. The paper outlines how mathematical optimization in general, and smart energy and power systems modeling in particular, lie at the heart of the energy informatics domain. The paper also identifies cyber-physical energy systems (CPES) and the Internet of Things (IoT), together with mathematical models, as the three main dimensions of energy informatics. The same three dimensions are key within the novel health-energy nexus as well. Health and energy represent physical spaces tightly interconnected with each other, where a wide variety of issues arise as a consequence of their interaction. The physical space comprising the sectors of health and energy can be investigated, understood, and controlled through modern mathematical and computer science techniques, which altogether are part of a so-called cyberspace. A cyberspace can successfully function through four main tasks that are strongly interconnected:

- Learn: understand the data
- Predict: forecast and generate new data
- Model: build technological mathematical optimization models
- Optimize: utilize the data and the models to make optimal decisions that can positively influence the physical space

Figure 8 represents this concept. By combining the physical space and the cyberspace outlined above, a novel Cyber-Physical Health-Energy System (CPHES) arises as a direct consequence of the pandemic.

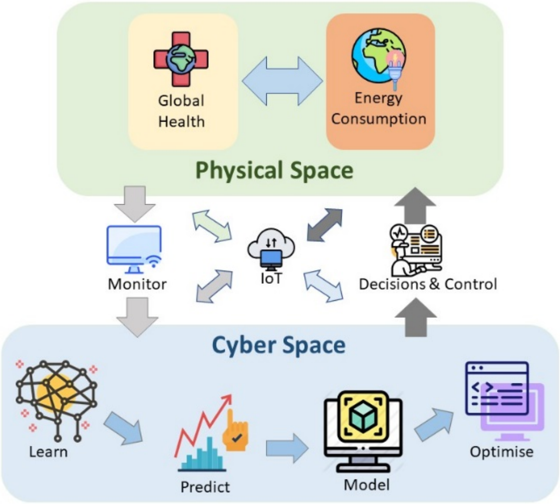

Figure 9: A novel Cyber-Physical Health Energy System (CPHES) arising from the health energy nexus as a consequence of the pandemic.

Once the learning and prediction tasks are over, the key is how to utilize this new knowledge to build mathematical models that represent the physical system. The knowledge, the data, and the models can be utilized within optimization tools, to make optimal decisions that can positively impact the physical space where the health and energy sectors are located. The concept of developing tools for predictions (i.e. machine learning) and utilize mathematical optimization to identify optimal decisions (both short term, or long term) over such predictions, marks the transition from a limited purely predictive analytics approach, towards a more advanced and complete prescriptive analytics approach [19].

The physical space and the cyberspace introduced above, are linked through two main tasks. "Monitoring" allows transferring data from the physical space into cyberspace. While "Decision and Control" take the decisions developed in cyberspace, and it implements them back into the physical space for the optimized management of the health-energy nexus. On top of the CPHES defined above, it is possible to add the Internet of Things (IoT). Through IoT, the CPHES can be connected to the internet, and decisions can be automatized and enhanced.

It is clear that mathematical modeling, with its intrinsic capability to contribute to decisions support systems tools in general, is a key subject within the health-energy nexus. Mathematical optimization has already been successfully applied to solve both power and energy systems-related problems [20]. In addition, mathematical optimization can be successfully utilized for optimal investment decision-making and operational management of VPP [21,22] within the nexus. The uncertainty behind the pandemic forthcoming developments can be tackled as well by optimization models. Resiliency and reliability issues that arise from different future energy demand projections can be addressed in particular with stochastic, multi-horizon optimization [23,24] and long-term scenario development at a qualitative level.

However, the complex and interdisciplinary nature of the nexus, requires the interconnection of different computer science subjects to tackle all the related challenges. Interdisciplinary approaches are therefore a must to address the main cascaded implications of the pandemic as discussed in the previous sections. An example of an interdisciplinary approach is presented in [25] where mathematical optimization is linked to other computer science subjects to address the consequences of data centers' energy consumption within the power systems. This can have strong implications on the health-energy nexus as well, since an increased energy consumption within data centers is one of the cascaded implications of the pandemic, as further discussed previously.

6 Towards an extended education-health-energy nexus

Figure 10 shows an extended nexus concept that arises in form of education-health-energy nexus. Indeed, education and consequently the knowledge that grows and spread through education, play an important role to understand, investigate, and address the current and future challenges posed by worldwide disasters like a pandemic.

Increased people's knowledge and awareness, lead to better actions both for personal health and for sustainable energy consumption. Better healthy habits (namely physical activity and nutrition) lead to a stronger immune system and therefore mitigate the pandemic spreading [26] and the consequent effects on human energy behavior. Better human energy behavior leads to better use of resources, reduced energy waste, and increased sustainability. It, therefore, mitigates the challenges on the power grids. Formal, non-formal, and informal education [27] are all key to lead the population towards healthier habits as well as more sustainable choices.

Raising awareness among the population is not enough, since the pandemic challenges on the health sector and the power system sector, need to be addressed also at more specialized technical levels, by researching and investigating new solutions and pathways. Higher education plays an important role from this point of view, providing skills and a proper mindset to understand advanced topics relevant for the health energy nexus.

As shown in Figure 8, three main pathways branch off from the education foundation: interdisciplinary teaching and research in general, the novel interdisciplinary domain of Energy Informatics in particular, as well as the key concept of VPP. The first two are tightly interconnected. The latter cannot be addressed alone but requires the first two as preparation paths to be fully understood and implemented.

Education within the energy informatics domain is still in its infancy, but recent works in literature have highlighted and discussed the importance of educating the future generation of energy informatics specialists, to address the future challenges of energy and power systems as well as the increasingly interdisciplinary needs of both in research and industry [28].

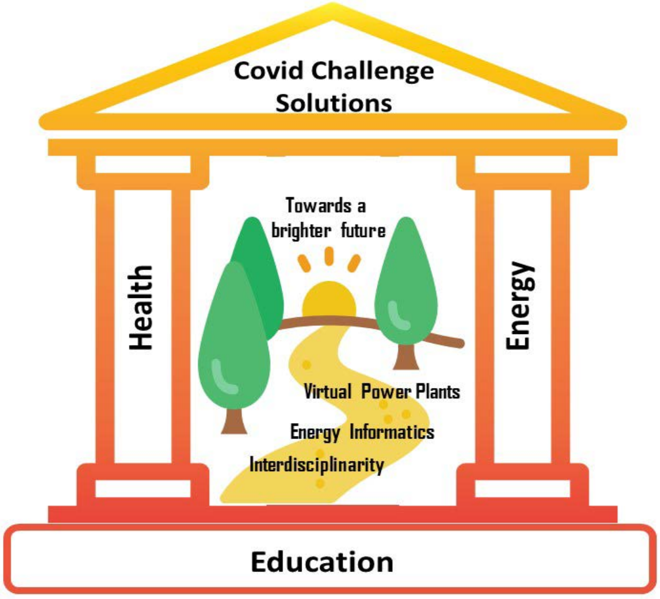

Figure 10: Key concepts of a forthcoming education-health-energy nexus.

7 The role of energy policies within the education-health-energy nexus

Energy policy is the set of measures through which the government addresses issues related to energy growth and usage. The latter includes energy production, distribution, and consumption. While it has been discussed that the health implications of COVID-19 affected the overall energy use and availability, it must be highlighted that a good portion of these changes was caused by the governments' responses and the policies that were pursued during the pandemic outbreak. Energy security of supply, as well as the quality and efficiency of energy services, are among key aspects that should be addressed by energy policies, especially under the threats of pandemic outbreaks like the one experienced with COVID-19.

Governments should identify appropriate strategies when responding to a pandemic outbreak so that short-term policy goals aimed at tackling an emergency, will not negatively impact medium to long-term policy goals aimed at ensuring the security of supply and high-quality energy services.

Governments should also increase their awareness of the implications of their measures not only at a national level but also at an international and global level.

Indeed, during the pandemic outbreak, the governments' responses and policies whilst being fairly ubiquitous, were not the same everywhere. Therefore, some countries have been hit much harder than others. However, it must be highlighted that the world nowadays is tightly interconnected, and no country is an island. Therefore, the different policies do not only directly affect the single country where they are developed, but they also indirectly affect the surrounding countries that are connected to it. This is particularly true when it comes to mobility constraints, which have been playing an important role in the energy consumption changes, as well as job allocation, during and after the pandemic. From the perspective of an interconnected world, even though policies might have been slightly different in each country, still their holistic effect impacted the overall energy system as a whole.

8 Conclusions

This work is about a topical issue, regarding pandemic implications on the energy and power systems, and the solutions to such issues, identified in VPP, Energy Informatics, and interdisciplinary education and research. The first part of the chapter aimed at reflecting on the implications of the COVID-19 pandemic on the energy sector. By understanding and verifying that indeed, certain health-related events affect energy consumption, the ambition was to introduce a new nexus concept to discuss how the two sectors can be interconnected. The implications of health problems linked to the pandemic uncertainty on the power and energy systems have been identified as a novel health-energy nexus. Such nexus has been illustrated and discussed. In addition, the new concept of Cyber-Physical Health-Energy Systems (CPHES) has been discussed and a further extension of the nexus towards education-health-energy nexus has been introduced.

COVID-19 is one specific health-related event that has been used to demonstrate that health can affect energy. However, the ambition of the chapter is to widen this aspect by reflecting on the broad implications that health and energy have on each other and expand the discussion towards key pathways that can help to overcome the challenges that may arise when health and energy meet each other. While the COVID-19 pandemic is one ongoing and topical instance that creates awareness of the health-energy nexus, many other different and unexpected events in the health sector may arise in the future causing similar implications on the energy sector. The ambition is therefore to learn from the pandemic, to identify broad pathways suitable to tackle future events within the health-energy nexus that may have similar implications.

It is clear that the proposed health-energy nexus has important implications for the energy and power systems as a whole. Therefore, the health-energy nexus as identified in this paper should be given more attention in the near future, and it should be considered as a priority at policy and political levels. This can be done by devolving funds to projects and research centers that tackle both sectors, health and energy, and that propose interdisciplinary solutions, with computer science as the main instrument to address the energy challenges. Suitable funding programs within the health-energy nexus should be developed and made accessible both for research purposes in academia and for applied purposes in the industrial world (namely, supporting start-ups aimed at developing novel products able to address the challenges of the health-energy nexus).

As mentioned in the previous sections, research and industry are tightly connected to education. Therefore, an education-health-energy nexus arises, where interdisciplinary education is the foundation to understand the subjects of health and energy and identify pathways to address the pandemic challenges. From this perspective, new interdisciplinary study programs should be developed to educate the new generation of energy informatics specialists, with adequate skills and mindset to take on the current and future challenges of energy and power systems under health-related pandemic uncertainty.

As discussed, energy policies played an important role during and after the pandemic outbreak. Since the world is highly interconnected, energy policies have not only direct national implications but also indirect international implications. From the perspective of an interconnected world, even though policies might have been slightly different in each country, still their holistic effect impacted the overall energy system as a whole. Therefore, the conclusions in terms of the relevance of a novel education-health-energy nexus as well as the value of pathways like VPP, Energy Informatics, and interdisciplinary teaching and research are universally valid.

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Icons have been procured from flaticon.com

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