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Bulk Energy Storage versus Transmission Grid Investments: Bringing Flexibility into Future Electricity Systems with high Penetration of Variable RES-Electricity

K. A. Zach and H. Auer

Abstract—**This paper analyses the flexibility provision for future electricity systems by bulk energy storage technologies (EST) as well as transmission capacity expansion based on selected European case studies. For this, future potentials of bulk EST in different European countries were estimated and matched with the spatial dispersion of future wind-deployment on country-level to be able to estimate the possible direct benefits of bulk EST implementation to balance the incumbent electricity system. Further on, the contribution of possible future transmission grid expansion for bringing together centers of variable wind generation and flexible generation was analyzed. In this context, an example of transmission expansion is presented: Central Western Europe and Nord Pool, where a cost / benefit analysis of transmission investments based on a welfare maximization approach is conducted. However, both technology options are needed to perfectly operate future European electricity systems with high shares of variable renewable electricity generation.**

Index Terms-- **Bulk Energy Storage, Transmission Grid, Investments, Flexibility, Variable Renewable Electricity Generation, Welfare Maximization**

I. INTRODUCTION

The significantly increasing deployment of variable renewable electricity generation (RES-Electricity) like wind (onshore, offshore) and solar photovoltaic (PV) is changing the way electricity systems have to be operated and managed in the future. Due to the high shares of variable RES-Electricity generation (mainly wind) future electricity systems will be increasingly "stressed" on several scales in time in both dimensions "amplitude" and "frequency". Therefore, proper technologies have to be implemented bringing necessary flexibility into future electricity systems. In general, the two most promising candidates in this context are:

(i) Bulk energy storage technologies (EST) like pumped hydro energy storage (PHES) and / or compressed air energy storage (CAES) and

(ii) Transmission capacity expansion providing access to flexible electricity generation technologies/markets.

The ability of bulk energy storage technologies to quickly discharge large amounts of stored electricity or to reduce loads during certain points in time throughout a day (e.g. providing regulating power, output smoothing, etc.) can mitigate many challenges which arise with high shares of variable RES-Electricity generation in the electricity system. On the one hand, additional variable RES-Electricity introduces more frequent price fluctuations in the energy system, on the other hand, lowers the price arbitrage between peak and off-peak periods, which is an essential parameter for the determination of the economics of energy storage.

The provision of flexibility for an electricity system has not necessarily to be covered inside the footprint of a single country / market region. Transmission grid expansion can bring synergies into neighboring electricity systems; besides others (e.g. market coupling, security of supply) transmission expansion can significantly contribute to connect centers of large-scale variable RES-Electricity generation with centers of flexible power generation in a European context.

II. METHODOLOGY

Future potentials of bulk EST in selected different European countries (Austria, Denmark, Germany, Greece, Ireland and Spain) are estimated in a wider context, i.e. not just "conventional" PHES, but also CAES and innovative PHES concepts (e.g. underground, sea water PHES, etc.) are taken into account.

In a next step, the identified bulk EST potentials are matched with the spatial dispersion of future wind deployment on country / region-level in Europe in order to be able to estimate the possible direct benefits of bulk EST implementation to balance the incumbent electricity system. For different selected cases, the economics of bulk EST are discussed under different constraints.

Then, the contribution of possible future transmission grid

K. A. Zach is with Institute of Energy Systems and Electrical Drives - Energy Economics Group, Vienna University of Technology, Gusshausstrasse 25-29/E370-3, 1040 Vienna Austria (email: zach@eeg.tuwien.ac.at)

H. Auer is with Institute of Energy Systems and Electrical Drives - Energy Economics Group, Vienna University of Technology, Gusshausstrasse 25-29/E370-3, 1040 Vienna Austria (email: auer@eeg.tuwien.ac.at)

expansion for bringing together centers of variable wind generation and bulk EST and / or flexible conventional generation (e.g. open- or combined-cycle gas turbines) in different European regions is analyzed. It is important to note, however, that transmission investments also have additional benefits (market coupling, security of supply), which are also taken into account.

In this context, an example of transmission expansion is presented: Central Western Europe and Nord Pool, where a cost / benefit analysis of transmission investments is conducted. It is based on a welfare maximization approach, which depends on the different wholesale electricity price levels. The methodology is implemented in MATLAB.

A. Flexibility Provision for future Electricity Systems by bulk Energy Storage Technologies

The estimation of the future potential of bulk energy storage technology implementation and its contribution to mitigate variability and intermittency caused by large-scale RES-E generation is not based on detailed modeling of the European electricity system, but rather based on a summary and synthesis of existing work, studies and modeling results on this topic. The time horizon for this potential analysis is mainly year 2020, 2030 and 2050.

At first, the geographical allocation of future potentials for bulk EST in the selected European countries is estimated based on the most relevant existing work and studies (on country-level as well as on European level). The following major categories are analyzed:

• Potential for extension of existing Hydro Energy Storage (HES) capacities to pumping mode: At present there exist many hydro reservoir/storage power plants without pumping mode. An extension to this mode (and simultaneously extension of the capacity in the generation mode) enables much more flexibility in the operation of a pumped hydro power plant meeting the future requirements / needs of market applications in the electricity system on several time scales. A rough empirical estimation of the future potential for extensions of hydro reservoir / storage power plants to the pumping mode in several European countries is conducted.

• Potential for new PHES capacities: A rough empirical estimation of the future potential for new PHES capacities in several European countries is conducted. Although the potential has been already exploited, there are important resources for new PHES capacities in different European countries.

• Innovative pumping approaches: A rough empirical estimation of the future potential of innovative approaches like the pumping of seawater, either on hills or in underground cavities, is considered. In this context installations are meant only for storage, not for primary hydro power production.

• Potential for new CAES capacities: At present, only two commercial CAES plants exist worldwide (a 290 MW unit was built in Hundorf, Germany in 1978; the second one is the 110 MW CAES power plant in McIntosh, Alabama, USA). Again, a rough empirical estimation of the future potential for new CAES capacities in the target countries is conducted. The key site-specific factor of the CAES technology is the availability of fitting underground mines or caverns (created inside salt rocks), on the one hand, and corresponding primary fuel (gas) supply, on the other hand.

After estimating the future potential for bulk EST, the geographical allocation of future large-scale wind deployment in several European countries for the year 2020, 2030 and 2050 are generated based on modeling results derived from the Green-X [1] RES-Electricity deployment simulation tools. Green-X provides future scenarios on annual RES-E capacities installations and electricity generation per country under a variety of different possible policy settings and constraints. The analysis of spatial dispersion of wind deployment in different European regions is a precondition to be able to conduct the following "matching" exercise.

Finally, the spatial dispersion of wind deployment and bulk EST potentials are matched on country / region-level in the different European countries in order to be able to roughly estimate the possible direct benefits of bulk energy storage technology implementation especially in those "stressed" electricity systems where the remaining fossil and / or nuclear power plant mix is less flexible.

Furthermore, also the impact of various other parameters in the technical potential or economic performance of energy storage and its role in the electricity system will be taken into account.

The main factors to be examined are listed here are, on the one hand, the contribution of possible future corridors on transmission interconnectors on ENTSO-E's transmission grid (based on published ENTSO-E documents and the "Energy Infrastructure" package) for bringing together variable / intermittent wind generation and bulk energy storage in different European regions (e.g. balancing "stressed" continental European electricity systems with bulk EST from PHES from the Alps and Scandinavia). On the other hand, also the amount of standby conventional generation that is expected to be available in the system and its relative costs on an annual basis compared to storage options are analyzed.

First examples for the results of this approach are shown in Fig. 1 and Fig. 2, where the residual load of Germany (wind generation excluded) in January 2010 and 2030 (with installed thermal power plants of 2015) is given. For the year 2030 two constraints were implemented: nuclear power plants are already phased-out in Germany (current policy status-quo) and no new conventional power plants are being built after 2015.

Whereas in 2010 the amount of bulk EST (or other flexible generation technologies), which is needed to, balance the electricity system is low (maximum amplitudes of 13 GW) the needed flexible capacities rise enormously until 2030. Especially in times of high wind feed-in (i.e. low residual load), high pumping capacities are needed (compare negative amplitudes of PHES of 20 to 30 GW). It is also clear to see, that in 2030 the installed power plant capacities are not enough for meeting the load and new flexible generation units will be needed (e.g. PHES, gas turbines etc.) [2].

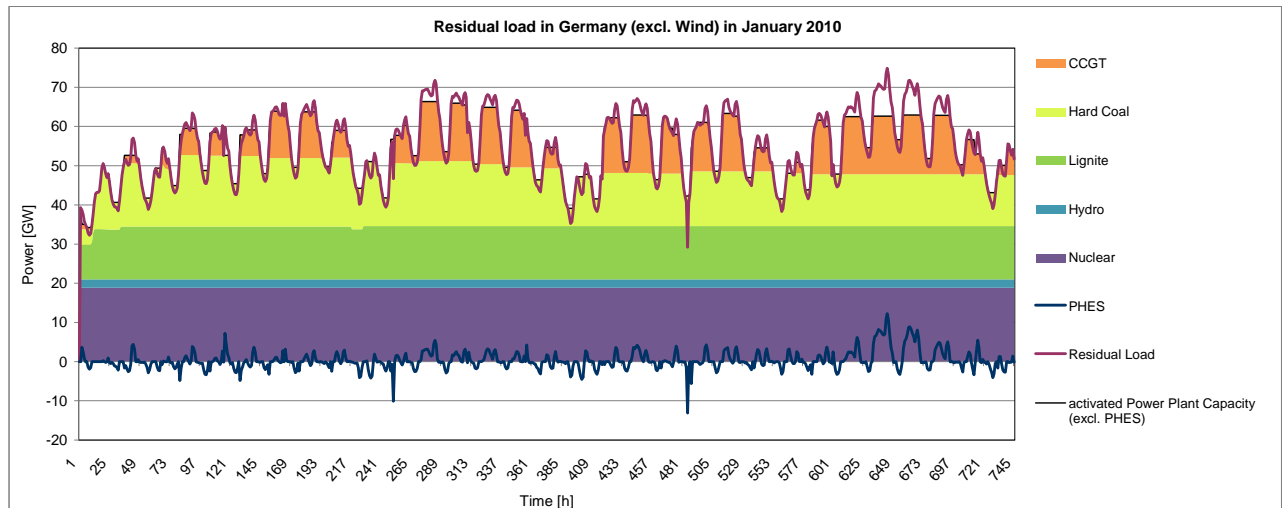Further analyses will be conducted within the IEE-project stoRE [8].

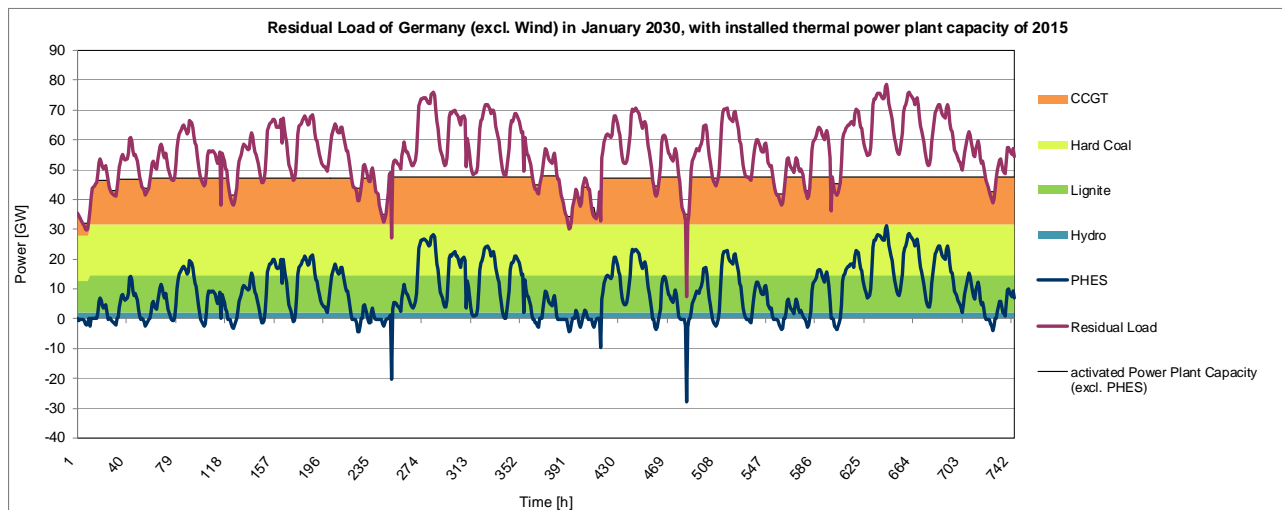Fig. 1. Residual load of Germany (wind generation excluded) in January 2010 [2]

Fig. 2. Residual load of Germany (wind generation excluded) in January 2030 with installed thermal power plant mix of 2015 [2]

B. Cost / Benefit Analysis of Transmission Grid Investments

Basic principles of price effects in case of market coupling of two markets with different wholesale price levels are shown in Fig. 3 and Fig. 4. The low price market "Nord Pool" (NP) is characterized by "cheap" and also excess generation capacity, especially flexible hydro power, whereas the high price market "Central Western Europe" (CWE) is characterized by "more expensive" generation capacity and less capacity margins. As a result of market coupling wholesale electricity prices increase (p_{NP} to p^*_{NP}) in the exporting market NP which goes along with an increase in producer surplus in market NP (area A and B in Fig. 3). On the contrary, prices decrease in the importing market CWE (p_{CWE} to p^*_{CWE}) resulting in increasing consumer surplus in CWE (area C and D in Fig. 4). In case that sufficient cross-border transmission capacities are available (no congestions) the price levels in CWE and NP converge (e.g. $p^*_{NP} = p^*_{CWE}$) and the social welfare (i.e. sum of producer and consumer surplus) would be maximized. In Fig. 5 this convergence of prices is shown in the combined net export-

/ import-curves of the two markets NP and CWE. The areas E and F represent the welfare gain in CWE and NP respectively if only a corridor with a capacity of $q_{Corridor\ 1,2}$ (i.e. congestion) is implemented.
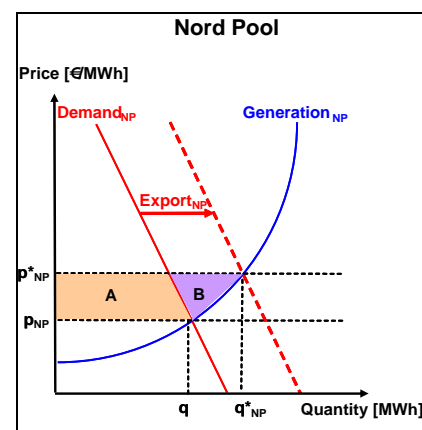

Fig. 3. Change of price level, producer and consumer rent in the exporting market Nord Pool [3]
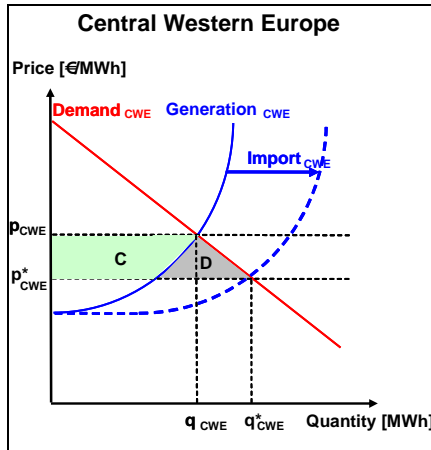
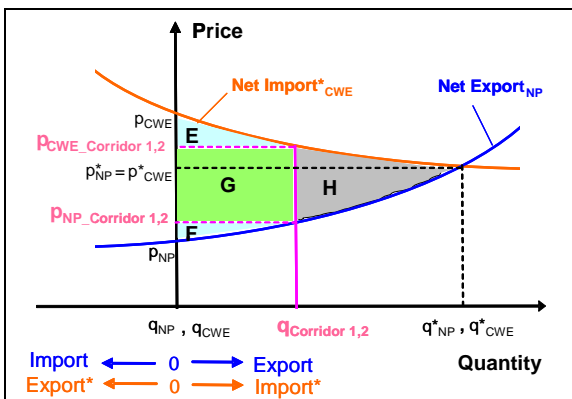Fig. 4. Change of price level, producer and consumer rent in the importing market Central Western Europe [3]

Fig. 5. Combined net export- / import-curves of the two coupled markets Central Western Europe and Nord Pool [3]

In this case of a congested transmission line coupling the markets NP and CWE the congestion rent of the corridor is the area G and the congestion cost (= welfare losses) is the area H. The congestion rent (or trading margin) is proportional to the price difference and the capacity of the corridor. This means that in case of maximum social welfare (e.g. $p^*_{NP} = p^*_{CWE}$) the congestion rent is zero, i.e. private operators of corridors (e.g. merchant transmission lines) have no interest of a price convergence in the coupled markets. For linear net export-curves the congestion rent is maximized in case of

$$q_{Corridor 1,2} = \frac{q^*_{NP}}{2} = \frac{q^*_{CWE}}{2} .$$

Therefore, to determine the social welfare gain in the coupled markets of CWE and NP the merit order curves of the two markets and their respective electricity demands have been developed. The merit order curves are established based on the composition of the electricity generation technologies [5] in the countries participating in the respective market (Austria, Swiss, Germany, France, Belgium and The Netherlands in CWE; Denmark, Finland, Norway and Sweden in NP) and an estimation of the short-run marginal generation costs of the different technologies. For each market four

different reference load functions were established based on hourly load values in the year 2009: summer / winter peak and summer / winter off peak. Fig. 6 and Fig. 7 show these established demand and generation curves for the CWE and NP market respectively. Since the Nord Pool market is characterized by shares of high hydro power, which has a higher availability in winter than in summer, two different linear approximation curves of the electricity generation were established, whereas the summer curve shows a higher slope.
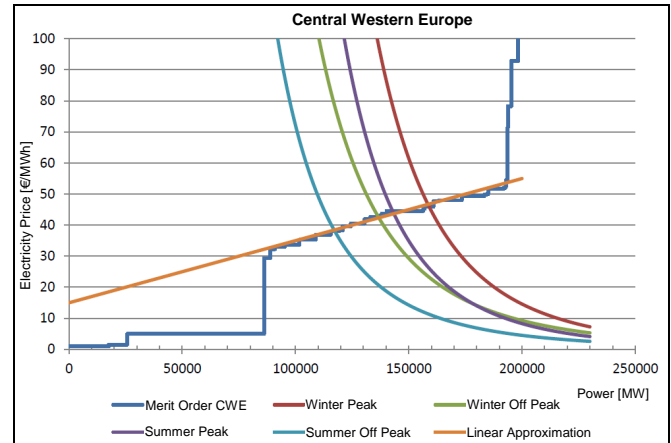

Fig. 6. Electricity generation and demand functions in the CWE market [4]
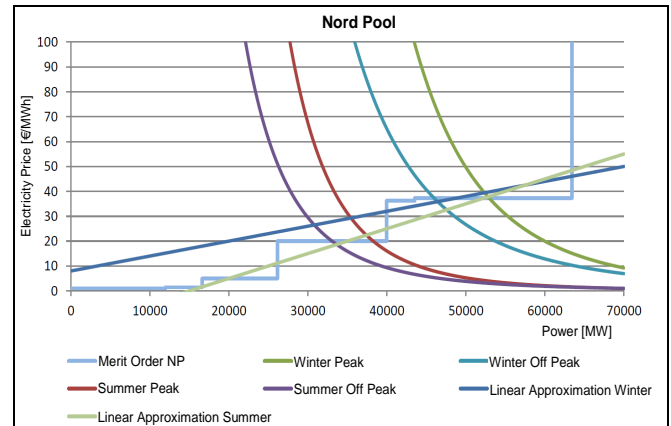

Fig. 7. Electricity generation and demand functions in the NP market [4]

Fig. 8 shows an example of the combined net export- / import-curves of the two coupled markets. These were established for all four different demand functions and the respective capacity optimums for the corridors were determined.
The corridor capacity optimums for the different reference cases are shown in Table I.

TABLE I
DETERMINED OPTIMUM CORRIDOR CAPACITIES FOR
MARKET COUPLING OF CWE-NP

Corridor Capacity [MW]	Winter Peak	Summer Peak	Winter Off Peak	Summer Off Peak	Average Value
Max. Welfare	10,290	21,480	9,420	20,920	15,528
Max. Congestion Rent	5,220	10,900	4,790	10,660	7,893

It can be seen, that the optimum capacities for winter and summer show great differences, which is due to high seasonal price differences in the isolated markets.
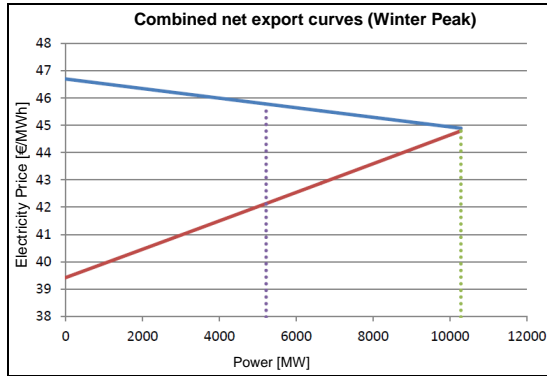
Fig. 8. Combined net export- / import-curves of the two coupled markets in the winter peak reference case [4]

The relative change of consumer surplus and producer surplus in case of complete market coupling (i.e. without congestion) is shown in Fig. 9. It can be seen that the producer surplus in the NP market can be increased by more than 80%, whereas the producer surplus in the CWE market falls for about 20%. Only small changes are observed in the consumer surplus, where the CWE market shows small increases. However, the CWE market additionally profits in terms of having access to more flexible (hydro power) generation in the NP market.
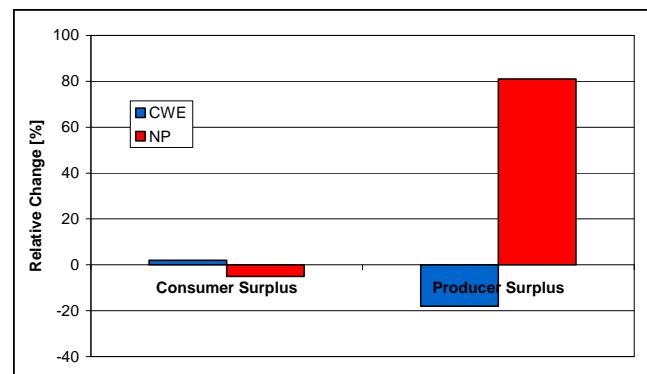

Fig. 9. Relative change of consumer and producer surplus in case of complete coupled markets NP-CWE [4]

To estimate the maximum annual congestion rent of the corridor NP-CWE the hourly congestion rents of a year have to be added up. Therefore, the maximum congestion rents of Table I, representing four different hourly reference cases in one year, are each multiplied by 2190 (annual hours divided by four) and added up. The estimated maximum annual congestion rent of the corridor NP-CWE results in about 570 M€ Further examples of case studies for cost / benefit analyses of transmission lines can be found in [6] and [7].

III. CONCLUSIONS

Both technology options, bulk EST as well as transmission grid expansion, are needed to perfectly operate future European electricity systems with high shares of RES-Electricity. The preferable measure (transmission expansion versus bulk EST) is dependent on the region in Europe and will mainly be decided via a cost / benefit analyses.

The first results of case studies in this paper show that also other technology options which increase the flexibility of the future electricity system (e.g. demand side management, additional flexibility from biomass / biogas and cogeneration plants, etc.) will be needed since the future potentials of bulk EST are limited. Further on, the effects of transmission grid investments in interconnecting corridors of markets were shown and shall provide some guidance in this context. Still, for both technology options, further analyses are necessary.

However, both technology options suffer from the same problem of low social acceptance, which will have to be overcome anyway.

IV. REFERENCES

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V. BIOGRAPHIES

Karl Anton Zach was born in Vienna (Austria), on December 3 1980. He is junior researcher and PhD candidate at Vienna University of Technology, Institute of Energy Systems and Electrical Drives - Energy Economics Group (EEG) since 2009. He holds a M.Sc. in Electrical Engineering from Vienna University of Technology. He is involved in many national and international research projects. His major fields of research are energy modeling and grid and market integration of distributed generation / renewable energy sources.

Hans Auer was born in Schmirn (Austria) on March 26 1969. He is senior researcher at Vienna University of Technology, Institute of Energy Systems and Electrical Drives - Energy Economics Group (EEG). He joined EEG in 1995. Hans' main research interests are electricity market analyses in general and grid and market integration policies of DG/RES-E technologies in this context in particular. In the last 16 years, Hans has been involved in many international and national projects in the renewable field for a variety of different clients. He has comprehensive teaching experience, a significant amount of energy conferences contributions worldwide and also authored around 40 peer reviewed scientific papers and book contributions.