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MODELLING AND SIMULATION OF ATMOSPHERIC BOUNDARY LAYER THERMAL STRATIFICATION: A SYSTEMATIC REVIEW

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Abstract. *This paper presents a systematic review on the state of the art in atmospheric boundary layer flow simulations, considering thermal stratification, and how this factor influences the prediction of wind turbine performance. To this end, the methodology applied follows the protocol presented by Dresch and coworkers, in the book "Design Science Research: research method for advancing science and technology", with the formulation of a review question, selection of keywords and survey for papers related to the theme on Scopus / Elsevier database. After validating whether the papers met the inclusion criteria, 18 papers were selected, and their results were synthesized according to the methodology applied (experimental or computational), and a bibliographic analysis was carried out. From the selected papers, 89% employed a computational methodology, which highlights the difficulty of carrying out experimental studies of wind turbines. Even though few authors have carried out the comparison between simulations considering, or not, thermal stratification, all have indicated accurate results for the models developed, which reinforces the importance of developing robust models, for greater accuracy of the results obtained. Bibliometric network analysis developed through VOSviewer software evidenced the authors with more publications and citations, as well as indicated that selected keywords are in agreement, since they were the most recurrent among the selected papers.*

Keywords: *wind power, atmospheric boundary layer, thermal stratification, computational fluid dynamics, systematic review.*

1. INTRODUCTION

With the advancement of technology, and the search for clean and renewable energy sources, the increase in the participation of wind farms in the world energy matrix is notable. Thus, planning for wind farms is necessary, and has as an important tool for the analysis of conditions, design and power output, the simulation by means of computational fluid dynamics (CFD).

Currently conducted simulations of air flow in wind farms focus mainly on modeling the atmospheric surface layer (ASL), which normally covers the lower 10% of the atmospheric boundary layer (ABL) (KOBBLITZ et al, 2015). In these cases, effects such as atmospheric stability are disregarded, with the intention of simplifying the models, using less computational power. Different studies, however, suggest that these considerations have a significant impact on the results obtained by the simulation, especially in places where there is a large annual temperature variation.

With the greater processing power of current computers, and in the search for greater reliability, simulations have been improved with the development of more robust models, capable of representing the phenomenon in an increasingly realistic way, providing more accurate data for the wind farm planning.

Thus, this systematic review seeks to map and analyze relevant works, with the intention of establishing the state of the art in atmospheric boundary layer flow simulations, considering thermal stratification, and how this factor influences the prediction of wind turbine performance.

To this end, the protocol presented by Dresch et al (2015), which will be presented in chapter II, was followed. The analysis of the results will be discussed in chapter III, and finally the conclusions will be exposed in chapter IV.

2. METHODOLOGY

This work followed the method proposed by Dresch et al (2015), who in turn compiled the protocol followed by different authors. At first, the review question and the conceptual framework were defined, which served as a structure to conduct the research.

The review question, which served as a starting point for this research, was: “What is the State of the Art in flow simulations in the Atmospheric Boundary Layer with thermal stratification and how does this factor influence the prediction of wind turbine performance?” The review was conducted with an aggregative strategy, since it sought to test a theory by collecting empirical observations made by other authors.

The papers selected to this review were separated according to the applied methodology: experimental or computational. Among those with experimental methodology, all papers related to the theme were considered, whether on laboratory scale (wind tunnel) or real scale. For those with computational methodology, a separation was made between those using a medium-fidelity model (such as WAsP, software used on a large scale in the wind industry), and high-fidelity models (with methods such as Lattice-Boltzmann, finite elements, finite volumes, among others). Among the high-fidelity models, the different methodologies for modeling turbulent flow (LES, RANS, DNS, etc.) were considered.

Scopus / Elsevier database was selected as the research source, being considered only works in English and carried out since 2000. The key terms selected for the research were: “WIND POWER” or “WIND FORECASTING”, “ATMOSPHERIC BOUNDARY LAYER” and “STRATIFICATION” OR “STRATIFIED”, in addition to the research area being limited to the energy sector. For the formulation of the search term, the Booleans “AND” and “OR” were used:

(TITLE-ABS-KEY ("WIND POWER" OR "WIND FORECASTING") AND TITLE-ABS-KEY ("ATMOSPHERIC BOUNDARY LAYER") AND TITLE-ABS-KEY ("STRATIFICATION" OR "STRATIFIED"))

A first assessment was made based on the abstracts of each paper, with the intention of discarding those that, despite presenting the searched terms, are not relevant to the review. After evaluating the abstracts, the studies that met the inclusion criteria were read in full. In this stage, the papers were evaluated according to the quality of the study's execution, adequacy to the review question and adequacy to the focus of the review. The results were synthesized by means of an electronic spreadsheet, where the methodology applied (experimental or computational) and the results obtained in each paper were identified.

2.1 Bibliometric analysis

To better understand the state of the art in research related to the impact of thermal stratification in atmospheric boundary layer simulations, bibliometric analysis of the selected papers were performed using VOSviewer, a software tool for visualizing and mapping science research (VAN ECK and WALTMAN, 2010).

This analysis was performed through the construction of bibliometric networks of indicators from the selected papers, which were exported from the Scopus database in an electronic spreadsheet, and later imported into the VOSviewer software. The relevance of the selected papers, authors and countries involved in the research was analyzed through maps generated by bibliometric coupling, with the number of publications and citations as indicators. In addition, a co-occurrence analysis of the keywords used in the selected papers was carried out to identify the main terms related to this research area.

3. RESULTS AND DISCUSSION

The first search in the Scopus / Elsevier database, considering only the proposed key terms, resulted in 73 papers, and the limitation of the research area for the energy sector reduced this number to 39. After the first analysis, by reading the abstracts of each article, 10 papers were disregarded because they did not meet the inclusion criteria, therefore not being relevant to this review. The second analysis, consisting of reading the full text of each article, excluded 11 other papers because, even though they contained the searched keywords, they presented problems regarding the quality of the study execution, adequacy to the review question and / or adequacy to the focus of the review. Thus, 18 papers were considered for this systematic review. Table 1 presents a summary of the information from the 18 selected papers.

Table 1. Summary of the selected papers.

First Author	Title	Year	Source Title
Abkar, M.	The effect of free-atmosphere stratification on boundary-layer flow and power output from very large wind farms	2013	Energies
Ali, N.	Anisotropy stress invariants of thermally stratified wind turbine array boundary layers using large eddy simulations	2018	Journal of Renewable and Sustainable Energy

Alinot, C.	Aerodynamic simulations of wind turbines operating in atmospheric boundary layer with various thermal stratifications	2002	ASME 2002 Wind Energy Symposium, WIND2002
Breedt, H.J.	Monin-Obukhov similarity theory and its application to wind flow modelling over complex terrain	2018	Journal of Wind Engineering and Industrial Aerodynamics
Castro, F.A.	One-way mesoscale-microscale coupling for the simulation of atmospheric flows over complex terrain	2015	Wind Energy
Dörenkämper, M.	The impact of stable atmospheric boundary layers on wind-turbine wakes within offshore wind farms	2015	Journal of Wind Engineering and Industrial Aerodynamics
El-Askary, W.A.	Modeling of wind turbine wakes under thermally-stratified atmospheric boundary layer	2017	Journal of Wind Engineering and Industrial Aerodynamics
Feliciano, J.	Generalized analytical displacement model for wind turbine towers under aerodynamic loading	2018	Journal of Wind Engineering and Industrial Aerodynamics
Gopalan, H.	Evaluation of Wray-Agarwal turbulence model for simulation of neutral and non-neutral atmospheric boundary layers	2018	Journal of Wind Engineering and Industrial Aerodynamics
Han, Y.	Large eddy simulation of atmospheric boundary layer flows over complex terrain with varying stability conditions	2017	35th Wind Energy Symposium, 2017
Ichenial, M.M.	Modeling of the atmospheric boundary layer under stability stratification for wind turbine wake production	2019	Wind Engineering
Kalvig, S.	Exploring the gap between 'best knowledge' and 'best practice' in boundary layer meteorology for offshore wind energy	2014	Wind Energy
Koblitz, T.	Computational fluid dynamics model of stratified atmospheric boundary-layer flow	2015	Wind Energy
Ohya, Y.	Laboratory and numerical studies of the atmospheric stable boundary layers	2008	Journal of Wind Engineering and Industrial Aerodynamics
Rados, K.G.	CFD modeling issues of wind turbine wakes under stable atmospheric conditions	2009	European Wind Energy Conference and Exhibition 2009, EWEC 2009
Sharma, V.	Time-adaptive wind turbine model for an LES framework	2016	Wind Energy
Siddiqui, M.S.	Numerical modeling framework for wind turbine analysis and atmospheric boundary layer interaction	2017	35th Wind Energy Symposium, 2017
Zhang, W.	Turbulent flow and heat transport over a two-dimensional steep hill: Wind-tunnel experiments	2015	33rd Wind Energy Symposium

Although most of the authors used data from wind measurement sites or previous experiments to validate the results, the vast majority of the analyzed papers focused on the development of a model for computational simulation of the flow in the atmospheric boundary layer with thermal stratification, as shown in Tab. 2. This highlights the difficulty of carrying out experimental studies of wind turbines, and reinforces the importance of developing robust models, for greater accuracy of the results obtained.

Table 2. Characteristics of the studies according to methodological aspects.

EXPERIMENTAL	11%
Laboratory Scale	100%
COMPUTATIONAL	89%
High Fidelity	94%
<i>RANS</i>	44%
<i>LES</i>	38%
<i>DNS</i>	6%
<i>Not identified</i>	12%
Medium Fidelity	6%

Among the works with high fidelity computational methodology, all used the Boussinesq approximation and the Monin-Obukhov theory of similarity for the modeling of thermal stratification of the atmospheric boundary layer. The parameters analyzed in each paper varied. While some authors have analyzed the impact of thermal stratification on turbulence and wake generation, others have analyzed its impact on energy production by wind turbines.

While the majority of the authors considered the results obtained to be satisfactory or qualitatively correct, only a few compared the results obtained with, and without, thermal stratification of the boundary layer, with the intention to analyze its impact in the results obtained, and defining if the addition of computational work brings a significant improvement for the model.

Alinot and Masson (2002) and Koblitz (2015) investigated through computational fluid dynamics the flow field around a wind turbine, using the Reynolds' averaged Navier-Stokes equations complemented by the $k-\epsilon$ turbulence model. The authors proposed an expression based on the Monin-Obukhov similarity theory for the closure coefficient related to the buoyancy production. Results obtained by Alinot and Masson (2002) show that this new expression has improved significantly the accuracy of the simulations in stable condition and the authors identified, through the simulations, that a maximum variation of approximately 7% in energy generation can be attributed to thermal stratification, which significantly impacts the prediction, especially in places where there is a large annual temperature variation.

Ichenial et al (2019) and El-Askary et al (2017) analyzed the effect of thermal stratification on the wake effect in wind farms. The results presented by Ichenial et al (2019) show that atmospheric conditions produce considerable losses, as they lead to greater turbulence perceived by one turbine positioned behind another. El-Askary et al (2017) found that there is a significant influence of the atmospheric condition on the behavior of the wake. In particular, the wake region becomes smaller with the decrease in atmospheric stability and, therefore, a greater wind energy in the wake region is observed in unstable conditions.

Sharma et al (2016) used a model with yaw control to simulate the behavior of a wind farm in a daily cycle, considering thermal variations of the atmospheric boundary layer. The results show that there is a significant potential to be converted during unstable periods, at the cost of designing wind turbines capable of adapting to the greatest variations in these periods. On the other hand, stable periods provide less power, but are more constant over time with a greater lateral shear induced by an increase in the change in wind direction with height.

Zhang et al (2015) conducted an experimental investigation of the flow over a steep 2-D hill in a wind tunnel with thermally controlled boundary layer. Both the test section floor and the air flow temperatures were independently controlled to achieve neutral, stable and unstable thermal stratification conditions. The results show that the fluid separation zone, downwind of the hill, is elongated by about 10 % in the stable boundary layer than that in the neutral case. Authors also observed that even though there is high turbulence intensity and Reynolds shear stress in the central region of the shear layer in both cases, stable stratification leads to a reduced turbulent intensity, by weakening turbulent mixing. Results obtained through this experiment provided reliable data sets for the development and validation of numerical models.

Abkar and Porté-Agel (2013) performed a set of large eddy simulations of fully developed wind farm atmospheric boundary layer, focusing on the influence of free atmosphere thermal stratification on the structure of the flow and power generation. The results indicate that thermal stratification is responsible for a reduction in the boundary layer height, leading to lower kinetic energy to be harvested by the turbines. For the wind farm arrangement considered, the power output of the wind turbines is reduced by about 35% when the temperature rate increases from 1 to 10 K/Km. Inspired by the results, the authors developed a one-dimensional model able to capture the effect of thermal stratification of the free atmosphere.

Ali et al (2018) analyzed, through large eddy simulations with and without a large wind farm, the effects of thermal stratification on the turbulent flow by the degree and nature of turbulent anisotropy. Results show that, in terms of anisotropy, the atmospheric boundary layer shows a narrower range of turbulence states for the model without wind turbines. When considering the wind turbine array, the turbulent mixing between the flow layers is enhanced and the distribution of states of turbulence characterized by the anisotropy maps increases.

Breedt et al (2018) developed an atmospheric boundary layer CFD model including the Monin-Obukhov Similarity Theory (MOST) to account for both the atmospheric stability and Coriolis force. The authors applied the model to measured data from a commercially proposed wind farm to analyze the prevalence and impact of atmospheric stability. The model proposed grants the ability to model more of the large-scale physical mechanisms of the atmospheric boundary layer, allowing for greater accuracy in the design of wind farms.

Castro et al (2015) extended the microscale code WINDIE, first developed for the simulation of neutrally stratified atmospheric boundary layer over complex topography, for the simulation of stable and unstable atmospheric flows. The code uses unsteady RANS and was extended to include stratification and rotational effects. Simulations with the code were performed for a time-varying atmospheric flow over a moderate complex terrain. The results were compared to those obtained with the Weather Research and Forecasting model with Advanced Research (WRF-ARW), developed by the National Centre for Atmospheric Research, and showed the ability to produce similar and, often better, performance indicators. Also, the simulation time for the WINDIE code case was less than 50% of the time necessary to run an equivalent WRF case.

Dörenkämper et al (2015) investigated offshore wind farm wake effects in marine boundary layer by means of dataset analysis and LES simulations. Simulations point the distance from the wind farm to the shore as being a crucial factor for the power production. Authors also observed that the rotors induce a mixing of the ABL, reducing its stability. The results reinforce the importance of enhanced wind turbine parametrization for better performance.

Feliciano et al (2018) used realistic inflow conditions for a diurnal cycle to explore the dependence of wind turbine leads and deformation with atmospheric stratification. Results show that lone standing wind turbine under stable stratification leads to the largest tower displacements, with a small standard deviation associated.

Gopalan (2018) proposed a MOST modification to the buoyancy term on the one-equation eddy-viscosity Wray-Agarwal (WA) turbulence model, to simulate the atmospheric boundary layer under different stratifications. Results show that even though the wind speed and turbulence profiles did not decay along the path for both neutral and non-neutral cases, there was a high difference in the prediction of turbulent viscosity near the ground for the non-neutral cases.

Han and Stoellinger (2017) implemented modifications to the boundary conditions of the OpenFOAM based flow solver SOWFA, developed by the National Renewable Energy Laboratory (NREL) to perform LES simulations of the atmospheric boundary layer over complex terrain under thermal stratification. By employing the modifications, the results showed some improvement over the previous model.

Ohya and Uchida (2008) investigated the effects of thermal stratification on the surface boundary layer, correspondent to de lower 10% of the atmospheric boundary layer. Authors performed experiments in a thermally stratified wind tunnel in parallel to direct numerical simulations with a finite-difference method. Experimental results showed that stable stratification attenuates streamwise temperature fluctuations, as well as streamwise and vertical velocity fluctuations. Also, for very strong stability cases, momentum and heat fluxes are nearly null over the whole boundary depth. Numerical results showed good agreement with the experimental ones.

Rados et al (2009) applied two different Navier-Stokes solvers to predict turbulence intensity and velocity deficits in the wake of a single wind turbine. One software uses the k- ϵ turbulence model, while the other uses the k- ω model, and in both cases the MOST was applied to account for atmospheric stratification. Authors observed that, for both neutral and stable conditions, the predictions can be improved by applying a smaller turbulent length scale, decreasing the turbulence decay ratio or increasing the turbulent dissipation rate near the turbine. Comparing the predictions with available data indicates that the different approaches lead to satisfactory results.

Siddiqui et al (2017) studied the effects of atmospheric stability through simulations on an OpenFOAM based solver, using a Multiple Reference Frame model. The authors found that under unstable stratification the buoyancy flux at the surface crates thermal instabilities that enhance the turbulent kinetic energy and the turbulence mixing, which speeds up the wake recovery in comparison to the stable and neutral conditions.

3.1 Bibliometric Analysis

The relevance of the selected papers was analyzed through a bibliographic network, generated by bibliographic coupling of the documents, seen in Fig. 1. Colors indicate the year of publication.

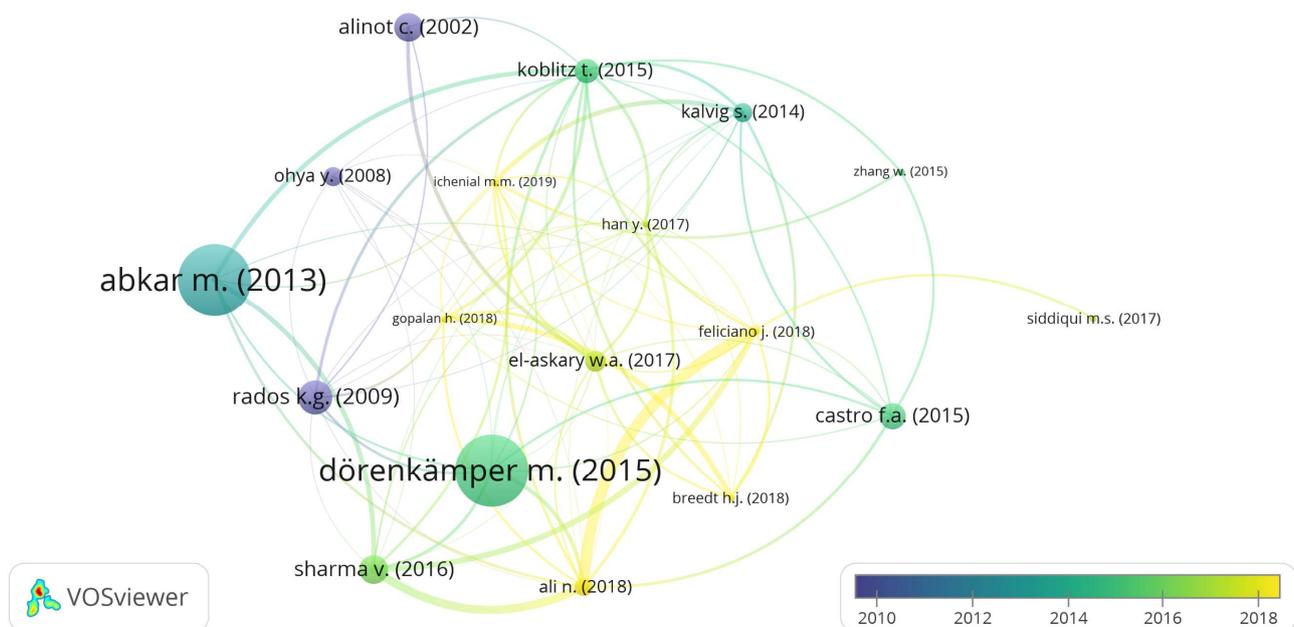


Figure 1. Papers bibliographic network
Created by the author on VOSviewer

In this map, bigger nodes indicate the most cited paper, while the proximity and thickness of the lines indicate a stronger link between two papers, determined based on the number of references they share. As this is a relatively new line of research, the bibliometric map shows what was expected: older works tend to have more citations, and the most current works are more related to each other, because they cite the same authors.

Similar to the previous analysis, two other maps were generated by bibliographic coupling, one of all the authors and the other of the countries from the selected papers, seen in Fig. 2 and Fig. 3 respectively.

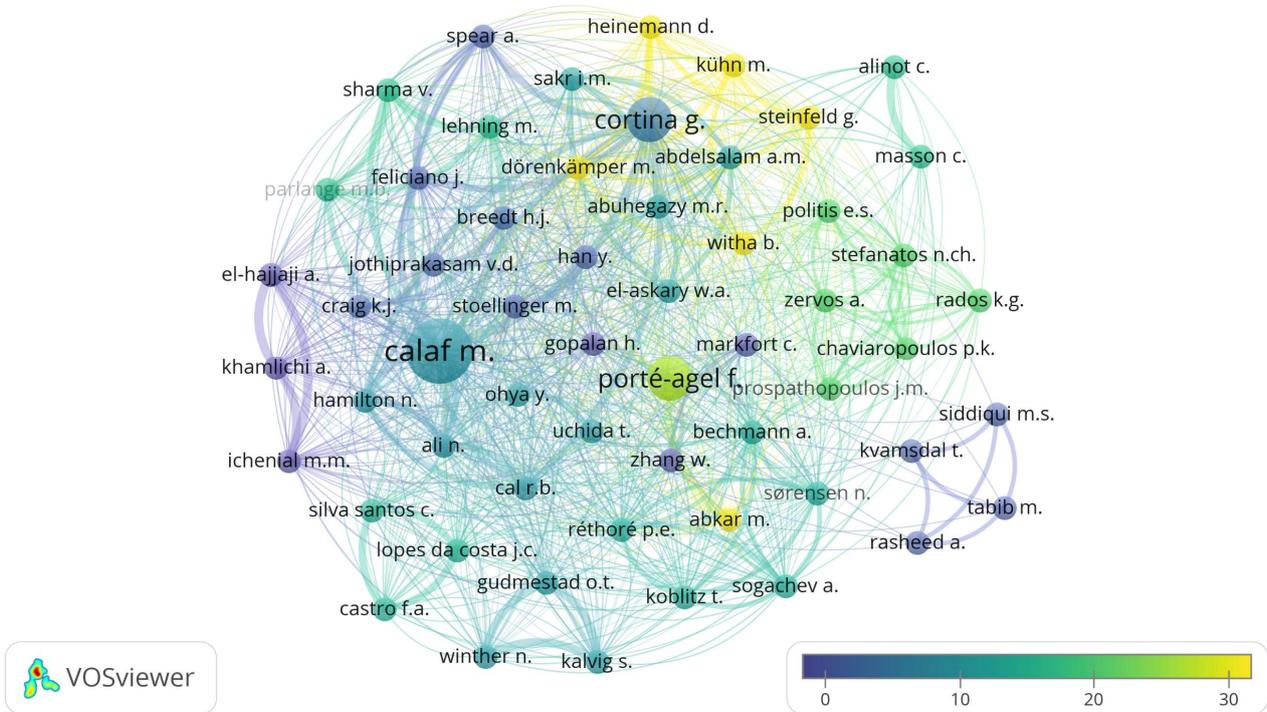


Figure 2. Authors bibliographic network
Created by the author on VOSviewer

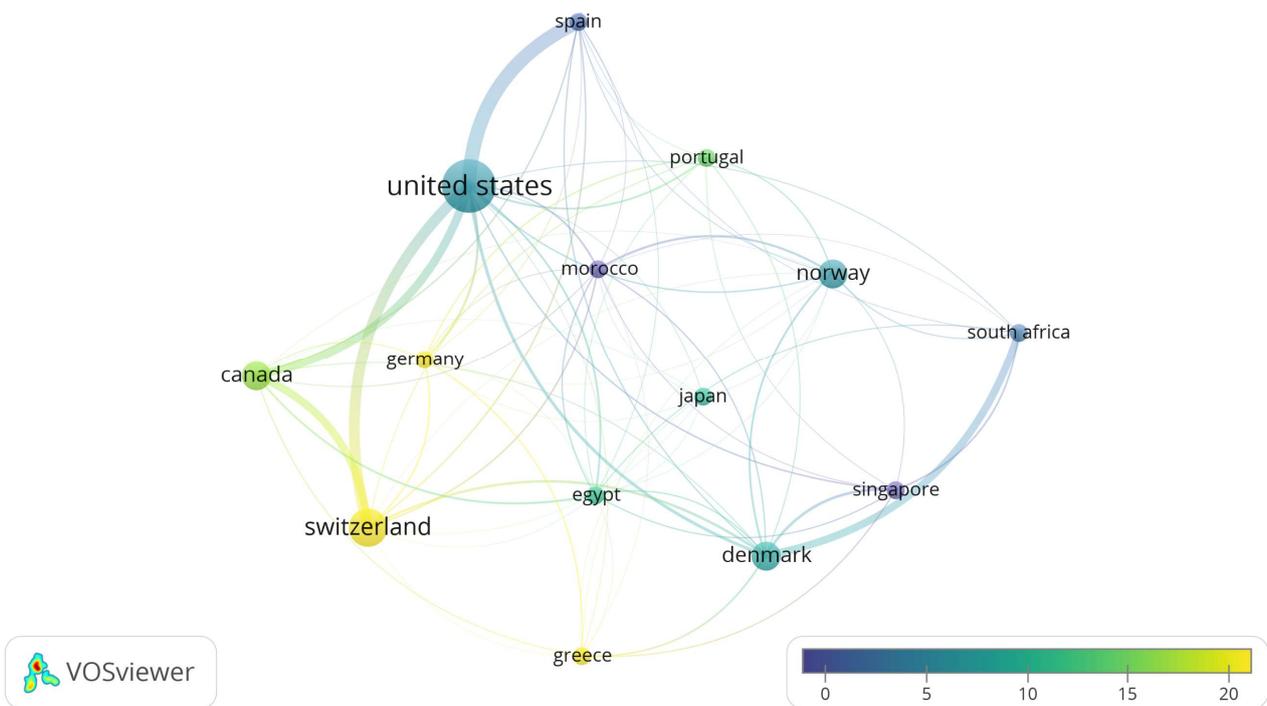


Figure 3. Countries bibliographic network
Created by the author on VOSviewer

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