

Curriculum Vitae

Professor Truls Eivind Norby



Role in project: Project manager ☐ Collaborator ☒

Personal information:

Full name: Truls Eivind Norby
Born: 22 June 1955
Nationality: Norwegian
Current position: Professor, Dept. Chemistry, Univ. of Oslo (UiO), Norway
Degree: 1986 Dr. Scient., Inorganic Chemistry, UiO
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Research positions and educational record:

1997 - Head of Section/Group for Solid-State Electrochemistry (FASE)
1995 - Professor, Department of Chemistry, UiO
1994 -1995 Associate professor, UiO
1987 - 1993 Post doc at UiO and researcher at the Nordic Energy Research Programme
1982 - 1986 Dr. Scient., March 1986, Dept. Chemistry, UiO, Norway.
1979 - 1981 M.Sc., Dept. Chemistry, UiO, Norway.

Mobility: Internat. visits/sabbaticals: U.Montpellier2 2015, UNSW 2009, U.Aveiro 2002, Chalmers 1993

Publications: 211 published/accepted articles in peer-reviewed international journals and books.

Research expertise and knowledge

Fields of research: Inorganic materials chemistry and solid-state electrochemistry. Expertise/national leadership: Functional ceramic materials; defects, transport, electrical properties and electrochemistry at high temperatures. Specialties/international leadership: Hydrogen defects; solid electrolytes; proton conducting solid oxide fuel cells and electrolyzers, electrochemical reactors, sensors; mixed ionic-electronic conductors for membranes and electrodes; ionics and electrochemistry of grain boundaries, electrode interfaces, and surfaces; DFT modelling of defect structures. Areas at the border to physics: Photoelectrochemistry and thermoelectrics. Current foci: Electrode kinetics, space charge defects at interfaces, exotic hydrogen defects; novel intermediate and ambient temperature proton conductors; solid-state photoelectrochemistry, novel phenomena at interfaces in thermoelectrics.

Major scientific achievements: Discovered many new classes of proton conducting oxides e.g. Ln_2O_3 ,^{1a} Al_2O_3 ,^b and LnXO_4 ^c and their defect chemistry, and the methodology of proton transport number determination.^d Pioneered hydration thermodynamics^e and parameterisation of grain boundary resistance in proton conducting oxides.^f Invented a nomenclature for defects in inherently disordered structures.^g Taken DFT modelling to complete defect structures under all conditions.^h Predicted and proved dominance of cation vacancies and protons in photocatalystsⁱ and did first-ever all-solid-state photocatalytic water splitting.^j Explored in-situ ammonolysis and behaviour of nitrogen defects in oxides^k and recently provided a complete picture of protons, Li defects, and lack of p-type conductivity in ZnO .^l Recently provided a complete model for conductivity in physisorbed water on ceramic surfaces.^m

Major innovation: Designed and commercialised (through NorECs AS) the ProboStatTM state-of-the-art cell for materials conductivity at high temperature and controlled atmospheres. Obtained as PI a patent for stable proton conducting oxides LnMO_4 which founded Protia AS (now CoorsTek Membrane Sciences AS) commercialising materials and processes based on ceramic proton conductors.ⁿ

Funding ID: Participant or leader/coordinator of the following recent research projects:

I coordinate the EU FCH JU project “ELECTRA” (7 partners, 2014-2017) and coordinated the EU FP7 ENERGY project “EFFIPRO” (7 partners, 2009-2012). Successful principal applicant and/or coordinator of 9 RCN projects during last 10 years, of which 1/3 national and 2/3 local (UiO/SINTEF Oslo). Additionally participated in 7 projects in Norway (3), Nordic region (1), EU (2), and with Japan (1).

^{1a}Norby, Kofstad *J. Am. Ceram. Soc.* 67 (1984) 786. ^bNorby, Kofstad *High Temp.-High Press.* 20 (1988) 345. ^cHaugsrud, Norby *Nature Materials* 5 (2006) 193. ^dNorby *Solid State Ionics* 28-30 (1988) 1586. ^eNorby *et al. Dalton Trans.* [19] (2004) 3012.

^fKjølseth...Norby *Solid State Ionics* 181 (2010) 268. ^gNorby *J. Korean Ceram. Soc.* 47 (2010) 19. ^hBjørheim, Stølen, Norby *PCCP* 12 (2010) 6817. ⁱNorby in “Solid State Ionics in the 21st Century”, Kim *et al.* (eds.), *MRS Bull.* 34 (2009) 923. ^jIwu, Galeckas, Kuznetsov, Norby *Electrochim. Acta*, 97 (2013) 320. ^kPolfus, Norby, Haugsrud *J. Solid State Chem.* 198 (2013) 65. ^lBjørheim, Kuwabara, Norby *J. Phys. Chem. C*, 117 (2013) 5919. ^mStub, Vøllestad, Norby, *J. Phys. Chem. C.* (2017) submitted, in revision.

ⁿMorejudo Norby, Serra, Kjølseth, *Science*, 353 [6299] (2016) 563.

Current projects as PI/coordinator, with funding source, project number, title (+acronym). Total budget in €:

- 2017-2020 EU MERA-NET, Governing Principles in Hydration of Mixed Conducting Oxides (GoPHy MiCo).
- 2016-2020 UiO Innovation Cluster; Thermoelectric materials for industrial applications (THERMiO).
- 2016-2019 RCN NANO2021, 250261, CO₂ utilization by formate dehydrogenase biocatalyst in a PhotoElectrochemical Cell (CO2BioPEC).
- 2015-2018 RCN NANO2021, 239211, Solar-based H₂ generation in novel photoelectrochemical cells using engineered hydrogenases as biocatalysts (PH2BioCat). € 1,535,060
- 2014-2017 RCN ENERGIX, 229705, Novel photoelectrocatalytic concepts for conversion of water, carbon dioxide, and nitrogen to fuels and chemicals (PlusUltra). € 1,332,168
- 2014-2017 EU FCH JU, 621244, High temperature electrolyser with novel proton ceramic tubular modules of superior efficiency...and lifetime economy (ELECTRA). € 3,789,000.
- 2012-2017 RCN CLIMIT, 224918, Self-healing ceramic membranes with increased lifetime for CO₂ capture in industrial processes and power production (SEALEM). € 1,435,026.

Current applications as PI/coordinator:

EU H2020 NMBP: 1. RCN FRIPRO TOPPFORSK: 1.

Current collaborations:

National: Projects NaProCs, 2D in collaboration with SINTEF; PlusUltra, FOXCET, SEALEM with NTNU and SINTEF; PH2BioCat, CO2BioPEC with Oslo University Hospital and SINTEF.

International: Abengoa and ITQ Valencia of CSIC (Spain), CRI (Iceland), Marion Tech. (France) all partners in the ELECTRA EU FCH project which I coordinate. Aalto Univ., Aveiro Univ., IIT Delhi. Gdansk, a.o. through ERA-NET NewIndigo and MERA-NET programmes. Overseas collaboration, co-publication, and exchanges with Universities in Japan (Tokyo, Kyoto, Nagoya, Kyushu, Sendai/Tohoku), US (Caltech, UCalifornia), and Sydney, Australia (UNSW). Industry collaboration with EU companies via EU project, with UiO and NTNU spinoffs (NorECs, Protia/CMS, CerPoTech, Baldur Coating a.o.) and CoorsTek, USA.

Membership in academic and professional committees and commissions of trust:

Member of the Norwegian Academy of Science and Letters, Norwegian Academy of Science and Technology, and Agder Academy of Science and Letters. International conference advisory boards: Solid State Ionics, Solid State Protonic Conductors. Editor, *Solid State Ionics* (Elsevier). Leader of Inorganic and Materials Chemistry group of the Norwegian Chemical Society.

Other professional activities: Leadership, Innovation, Teaching

Leadership: established and headed top-tier crossdisciplinary *FERMiO* (Functional Energy Related Materials in Oslo) from 2007 after reaching the final of the national CoE call. Leads research group for Solid-State Electrochemistry (FASE). Established *Gemini centre* for collaboration in solid-state electrochemistry between UiO and SINTEF Chemistry&Materials starting 2013. **Innovation:** Founded *NorECs* Norwegian Electro Ceramics AS (www.norecs.com) in 2001, developing, manufacturing and selling scientific equipment and functional materials worldwide. Initiator and board member of *Protia* AS 2008 (recently *CoorsTek Membrane Science Group Norway* AS), which develops ceramic proton conducting fuel cells and gas separation membranes for petrochemical fuel processing. Awarded *UiO's Innovation Prize* 2012. **Teaching:** 6 UiO courses; main lecturer of entry level (MENA1000) and advanced (KJM5120/9120) courses.

Supervision of PhD and MSc students:

Graduated to date: 31 PhD and 53 MSc. I currently supervise 3 MSc students, 6 PhD students, and 5 post doc fellows. Most graduated students have pursued next level studies. Two have university professorships. Others take research positions in one of the biggest European research institutes, SINTEF, or in other institutes, like the Institute for Energy Technology (IFE) or Det Norske Veritas (DNV), or in major Norwegian industries, such as Statoil, Renewable Energy Corporation (REC) and Elkem, as well as in SMEs.

International conference and workshop organisation

Conferences organized last 10 years are listed in the 10-year track record, e.g. International workshop on BZY, Oslo, March 24-27, 2015, and symposia in major conferences. Before that, I emphasize in particular my organization as chairman of the 8th International Conference on Solid State Protonic Conductors (SSPC-8) August 1996, Gol, Norway. In 2016 I organised as co-chair the 18th International Conference on Solid State Protonic Conductors (SSPC-18) September 2016, Oslo, Norway. IN 2017 I co-organise symposia at SSI-2017 and EUROMAT-2017.

10-Year track-record

Total 211 printed/accepted peer-reviewed articles, plus 1 granted and 4 pend. patents. From WoS/Scopus: Citations & h-index all years: 211 articles, 5895/4680 citations with/without self, average 26, **h-index: 37**. Citations & h-index 2007-2017: 120 articles, 1660/1452 citations with/without self, average 14, h-index: 22. Google Scholar: Citations all years/since 2012: 7733/3896. h-index: 45/33. I10-index: 147/108.

10 selected top publications/research achievements last 10 years (citations in parenthesis)

1. Novel proton conductors: R. Haugrud, T. Norby, "Proton conduction in rare earth ortho-niobates and ortho-tantalates", *Nature Materials*, 5 (2006) 193 (319). Discovery of a new class of proton conductors, leading to granted patent, startup of company Protia AS (now CoorsTek Membrane Sciences (CMS) AS), several follow-up RCN projects, EU project, innovation prize awarded to Norby and international research focus on LaNbO_4 .

2. Space charge: C. Kjøseth, H. Fjeld, P.I. Dahl, C. Estournès, R. Haugrud, T. Norby, "Space charge theory applied to the grain boundary impedance of proton conducting $\text{BaZr}_{0.9}\text{Y}_{0.1}\text{O}_{3-\delta}$ ", *Solid State Ionics*, 181 (2010) 268. (123). Reveals for the first time that the grain boundary resistance in high temperature proton conductors is due to an intrinsic core charge and consequent space charge layers with charge carrier depletion, and not impurity phases as assumed before.

3. Structure and defects: A. Magraso, J.M. Polfus, C. Frontera, J. Canales-Vazquez, L-E. Kalland, CH. Hervoches, M. S. Islam, T. Norby, R. Haugrud. "Complete structural model for lanthanum tungstate: a chemically stable high temperature proton conductor by means of intrinsic defects", *Journal of Materials Chemistry*, 22 (2012) 1762 (75). Provides the breakthrough in understanding the new class of mixed oxide ion, proton, and electron conducting rare earth tungstates, after years of confusion in the world literature.

4-5. Cation diffusion: J.B. Smith, T. Norby, "On the steady state oxygen permeation through $\text{La}_2\text{NiO}_{4+\delta}$ membranes", *J. Electrochem. Soc.*, 153 (2006) A233 (67). - J.B. Smith, T. Norby, "Cation self-diffusion in LaFeO_3 measured by the solid state reaction method", *Solid State Ionics*, 177 (2006) 639 (43). The first of these papers pioneers the scientific investigation of oxygen transport through the $\text{La}_2\text{NiO}_{4+\delta}$ class of mixed oxide ion electronic conductors, patented by Norsk Hydro/Statoil for air separation in oxyfuel-type CO_2 -free gas power plants. The second paper is the start of a series of investigations and publications, continuing today, where we uniquely measure the membrane life-time-limiting cation transport by solid-state reaction, interdiffusion, and chemical tracer-diffusion in the above-mentioned $\text{La}_2\text{NiO}_{4+\delta}$ and – here – perovskites ABO_3 . The papers reveal that enhanced diffusion along grain boundaries for the B-site cation (e.g. Ni or Fe) is the fastest and most detrimental process. While cation diffusion eventually leads to membrane walkout, demixing, and decomposition, the understanding of the phenomena has also led to discovery of two potential routes to self-healing membranes in patent, applications, and granted RCN project.

6-7. First principles calculations: The power of our DFT computational approach is disseminated in recent papers by T.S. Bjørheim *et al.* 2010-2015, e.g. T.S. Bjørheim, A. Kuwabara, T. Norby, "Defect chemistry of rutile TiO_2 from first principles calculations", *J. Phys. Chem. C*, 117 (2013) 5919 (24). We also use DFT increasingly in combination with advanced structural analyses, see above, and electrical characterisation, e.g. T. S. Bjørheim, S. Erdal, K.M. Johansen, K.E. Knutsen, T. Norby, "H and Li related defects in ZnO and their effect on electrical properties", *J. Phys. Chem. C*, 116 (2012) 23764 (22).

8. Semiconducting oxides; thermoelectrics and photoelectrochemistry: M. Schrade, H. Fjeld, T. Finstad, T. Norby, "Electronic transport properties of $[\text{Ca}_2\text{CoO}_{3-\delta}]\text{q}[\text{CoO}_2]$ ", *J. Phys. Chem. C*, 118 (2014) 2908 (20). This and similar papers on oxide thermoelectrics and photoelectrochemistry display the cross-disciplinary interest in the physics, chemistry, and photoelectrochemistry of semiconducting oxides.

9. Electrodes: R. Strandbakke, V. Cherepanov, A. Zuev, D.S. Tsvetkov, C. Argiris, G. Sourkouni-Argiris, S. Prünke, T. Norby, "Gd- and Pr-based double perovskite cobaltites as oxygen side electrodes for proton ceramic fuel cells and electrolyser cells", *Solid State Ionics*, 278 (2015) 120-32. First complete model to understand oxide electrodes for proton ceramic fuel cells and steam electrolyzers.

10. Electrochemical reactors: S.H. Morejudo, R. Zanón, S. Escolástico, I. Yuste-Tirados, H. Malerød-Fjeld, P.K. Vestre, W.G. Coors, A. Martínez, T. Norby, J.M. Serra, C. Kjøseth, "Direct conversion of methane to aromatics in a catalytic co-ionic membrane reactor", *Science*, 353 [6299] (2016) 563 (11). The paper demonstrates the application of proton ceramic oxides in a process developed by the UiO spin-off company Protia AS (now CMS AS) in Oslo.

Chapters and collective volumes and books (invited reviews):

T. Norby, R. Haugrud, "Dense ceramic membranes for hydrogen separation", in *Nonporous Inorganic Membranes* (Sammells, Mundscha, eds.), Wiley-VCH, Weinheim, 2006, ISBN 3-527-31342-7, pp. 1-48.
 T. Norby, "Proton conductivity in perovskite oxides", in *Perovskite oxide for solid oxide fuel cells* (Ishihara, ed.), *Fuel Cells and Hydrogen Energy*, Springer, ISBN 978-0-387-77707-8 (2009) 217-241.

Granted patents

Total of 4 patent applications filed as PI and first inventor, of which 3 pending and 1 granted, the latter being: T. Norby, R. Haugrud, S. Marion, K. Wiik, M.-A. Einarsrud, Ø. Andersen, R.A. Strømme, T. Grande, "Proton Conductors." *International patent publication number WO 2006/066918, filed December 22, 2005, date of publication March 18, 2009.* This patent describes the discovery of acceptor-doped LaNbO_4 and LaTaO_4 as stable proton conductors in humid atmospheres for use in fuel cells, electrolyzers, and sensors. It led to the start of spin-off company Protia AS and a thriving branch of solid state ionics research on LaNbO_4 .

Invited lectures at international conferences:

70 scientific lectures at international conferences over last 10 years (2007-2017), of which 45 invited.

10 examples of invited lectures 2013-2017:

1. Norby, T., "Self-healing ceramic membranes", Int. Conf. Solid State Ionics (SSI-2017), Padua, Italy, 2015-06-18 – 2017-06-23.
2. Norby, T., Løken, A., "Proton defect interactions in oxides", e-MRS 2016 spring, Lille. Symposium D,, 2016-05-02 – 2016-05-06.
3. Norby, T., "Inorganic protonic conductors", 32nd PSI Int. Symp. Electrochem, PSI, Villigen, 2016-04-27.
4. Norby, T. *et al.* "Model and methodology for investigation of oxygen electrodes on BZCY electrolytes" Int. Conf. on Solid-State Protonic Conductors 17 (SSPC-17); 2014-09-14 - 2014-09-19
5. Norby, T. "Protons and Exotic Hydrogen Species in Oxides - Presence, Effects, and Applications, I²CNER International seminar series, Kyushu, 2014-03-14.
6. Norby, T.; Kjølseth, C.; Coors, W.G.; Fontaine, M-L., "Materials and tubular membranes for applications of proton conducting ceramics". Int. Conf. on Solid State Ionics 19; Kyoto, 2013-06-06.
7. Norby, T. "Hydrogen diffusion in oxides". Invited. Diffusion in Solids and Liquids 2012 (DSL2012), Special Session 10 Hydrogen kinetics; Istanbul, 2012-06-25.
8. Norby, T. "Ionic conduction in oxides with fluorite-related structures, inherent oxygen deficiency, and peculiar defect chemistries". Invited. Int. Workshop on Nonstoich. Compounds V; Taormina, 2012-09-23.
9. Norby, T. "Materials and interfaces for PCFCs based on $\text{La}_{28-x}\text{W}_{4+x}\text{O}_{54+3x/2}$ and Ca-doped LaNbO_4 electrolytes." Invited. Int. Conf. on Solid State Protonic Conductors 16 (SSPC16); Grenoble, 2012-09-10.
10. Norby, T. "Secondary Transport Phenomena in Ceramic Membranes under Electrochemical Potential Gradients." Invited. MS&T 2012, Int. Symp. Defects, Transport and Related Phen.; Pittsburgh, 2012-10-07.

Organisation of International conferences in the field of the applicant, from 2010

1. 18th Int. Conf. on Solid State Protonic Conductors (SSPC-18) September 2016, Oslo, Norway. Co-chair.
2. International workshop on BZY, March 24-27, 2015, Oslo, Norway. Organizer.
3. Solid proton conductors, Symposium F, E-MRS Spring 2012 (in honour of G. Alberti), Strasbourg. May 14-17, 2012. Co-organizer.
4. 7th Int. Petite Workshop on the Defect Chemical Nature of Energy Materials. March 14-17, 2011, Kongsberg, Norway. Chairman. Proceedings in *Int. J. Hydrogen Energy*, **37** [9] (2012).
5. 2nd Nordic Symposium on Functional Energy Related Materials; Science and Applications of High Temperature Proton Conductors, April 12-15, 2010, Storaas, Norway. Chairman.

International Prizes/Awards/Academy memberships

University of Oslo Innovation Prize 2012.

DnBNOR national innovation prize for 2010 awarded Protia AS for their proton membrane GTL process.

Elected member of the Norwegian Academy of Science and Letters, Norwegian Academy of Science and Technology, and Agder Academy of Science and Letters.

Memberships to Editorials Boards of International Journals.

Editor of *Solid State Ionics* (Elsevier, www.journals.elsevier.com/solid-state-ionics/)

Examples of leadership in industrial innovation or design

Companies: Started NorECs AS, initiated Protia AS (now CoorsTek Membrane Sciences AS (CMS)), and worked for and supported the startups of CerPoTech AS and InNano AS. Hold trademark for ProboStat™ and patent for Probble as products of NorECs and a patent as basis for Protia/CMS AS.