

## How did the General Purpose Technology 'Electricity' contribute to the Second Industrial Revolution (I): The Power Engines.

van der Kooij, Bauke

**Publication date**

2016

**Document Version**

Final published version

**Citation (APA)**

van der Kooij, B. (2016). *How did the General Purpose Technology 'Electricity' contribute to the Second Industrial Revolution (I): The Power Engines.*

**Important note**

To cite this publication, please use the final published version (if applicable).  
Please check the document version above.

**Copyright**

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

**Takedown policy**

Please contact us and provide details if you believe this document breaches copyrights.  
We will remove access to the work immediately and investigate your claim.

# How did the General Purpose Technology 'Electricity' contribute to the Second Industrial Revolution (I): The Power Engines.

B.J.G.van der Kooij

Guest at the University of Technology, Delft, Netherlands  
Jaffalaan 5, 2628 BX, Delft, the Netherlands

## Abstract

The concept of the General Purpose Technology (GPT) of the late 1990s is a culmination of many evolutionary views in innovation-thinking. By definition the GPT considers the technical, social, and economic effects of meta-technologies like steam-technology and electric technology. This paper uses Schumpeter's concept of 'cluster on innovations' to create insight in the nature of these GPT's. Three case studies are presented: 'The invention of the Steam Engine', 'The invention of the Electromotive Engine' and 'The invention of Electric Light'. For the GPT-Steam and the GPT-Electricity, the power technologies, we found that these inventions— better 'clusters of innovations'— were the core elements in the technical contributions to both Industrial Revolutions. It were the innovations in applications of electricity—like in electric light and electric appliances— that made 'electricity' contribute so greatly to the Second Industrial Revolution.

## Keywords

General purpose technology, technological innovation, cluster of innovation, innovation, history of technology.

JEL: N7, O31, O33, O40,

Drs.Ir.Ing. **B.J.G. van der Kooij** (1947), former professor in the Management of Innovation, politician and entrepreneur, is currently pursuing a PhD degree at the University of Technology of Delft, the Netherlands. He can be reached by e-mail at [b.j.g.vanderkooij@tudelft.nl](mailto:b.j.g.vanderkooij@tudelft.nl) or [vanderkooij@ashmore.nl](mailto:vanderkooij@ashmore.nl) and at 0031 651 428860. Correspondence can be addressed to: Vinkenlaan 33c, 3722AH Bilthoven, The Netherlands.

Conflict of Interest: The author declares that he has no conflict of interest.

Figures: All figures are created by the author.

## 1. Introduction

In the eighteenth century, developments in steam technology — among others in metallurgy, textile manufacturing, and other fields — contributed to the First Industrial Revolution. Developments in electric technology, together with others in steel and chemicals, did the same in the Second Industrial Revolution. The nineteenth century saw an avalanche of technological invention based on the new phenomenon of electricity. It attracted scholarly observation that created insight in the role of technology in economic growth (Gilfillan, 1935; Schumpeter, 1935; Usher, 1929). In the mid-1900s others scholars, observing the same phenomena did the same, talking about those ‘inventions’ (Griliches, 1957; Maclaurin, 1953; Scherer, 1965; Schmookler, 1966).

More recently — i.e. in the last decades of the twentieth century — scholarly attention has been paid to ‘innovation’ (David, 1975; Freeman, 1985; Ruttan, 2000). From many disciplines many views, theories and models have sprouted from the domain of Innovation Research. Among those we find the paradigm of the *General Purpose Technologies* (GPT) (Bresnahan & Trajtenberg, 1995; David & Wright, 1999; Helpman, 1998; Jovanovic & Rousseau, 2005; Lipsey, Carlaw, & Bekar, 2005). The GPT-concept tries to explain the major changes that took place in societies and economies where a dominant technology results in creating considerable novelty and is having a major impact on society and economy.

We observed in detail the same phenomena as those earlier scholars (B.J.G. van der Kooij, 2015; B.J.G. van der Kooij, 2015b, 2015c). In this paper we will focus on ‘technology’ in the GPT-concept. We will present our analysis by outlining shortly the invention of the steam engine, and more extensively the invention of the electromotive engine and the invention of the electric light. We choose for ‘electricity’ because it is supposed — both being power processing technologies — to have contributed to the Second Industrial Revolution in a similar way as steam technology contributed to the First Industrial Revolution (Mokyr, 1990, pp. 83-92, 122-126).

## 2. Theoretical framework

Innovation scholars - those economic, sociological and management scholars who look at the Domain of Innovation Research - have in common that they observe 'change and novelty' created by technology having impact in economy and on society. Each scholar having its own concept, perspective, unit of analysis and definition (Kooij, 2013b). For our observations we borrowed the following concepts:

**Schumpeter's Innovation concept:** The topic 'invention/innovation' is en vogue already for a century;

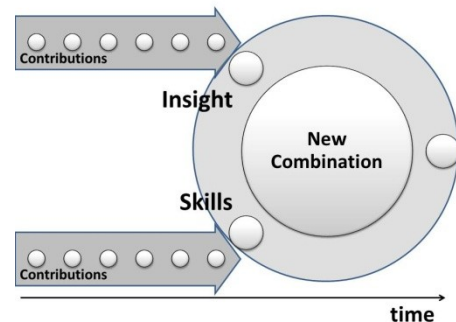
among many historians, evolutionary economists, sociologists, and managerial gurus. One of them was the economist Joseph Alois Schumpeter (1883-1950). For Schumpeter Innovation was the result of 'New Combinations' realized by the entrepreneur (Schumpeter Mark-I); "[...] *innovation combines factors in a new way, or that it consists in carrying out New*

*Combinations, [...]*" (Schumpeter, 1939, p. 84). He saw innovation as quite different from invention: "Although most innovations can be traced to some conquest in the realm of either theoretical or practical knowledge, there are many which cannot. Innovation is possible without anything we should identify as invention, and invention does not necessarily induce innovation, but produces of itself [...] no economically relevant effect at all." (Schumpeter, 1939, p. 80). His contemporary Abbott Payson Usher (1883-1965) —

using the words 'discovery' and 'invention' by each other — saw it, after analyzing mechanical innovations over time

(Usher, 1929), as the cumulative synthesis. "Invention finds its distinctive feature in the constructive assimilation of preexisting elements into new syntheses, new patterns, or new configurations of behavior." (Usher, 1929, p. 11). The new combination was the result of the 'act of skill' and the 'act of insight' (Figure 1): "Practically, we characterize as an invention only some concept or device that represents a substantial synthesis of old knowledge with new acts of insight." (Usher, 1955, p. 530).

Schumpeter's definition reflects the combination-approach in invention-thinking at the beginning of the twentieth century up to the 1950s. It was not the only definition of innovation — as we have explored this heterogeneity elsewhere (Kooij, 1988, 2013a) —, but we would like to suffice with defining innovation for the moment in the spirit of Schumpeter: *Innovation is the new combination that creates new products, markets, organizations and production methods.*



**Figure 1: Synthesis-thinking where Innovation is the new combination: the result of the act of insight combined with the act of skills.**

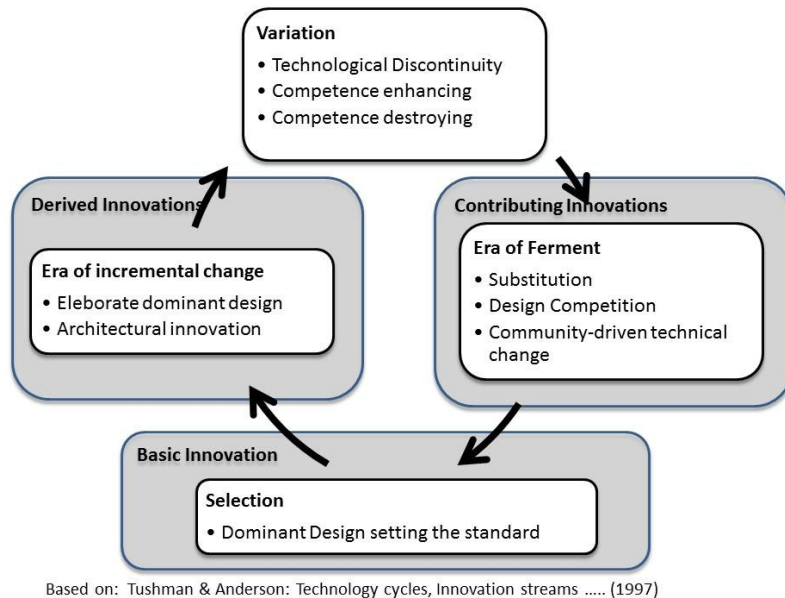
## Anderson's & Tushman's

### Dominant Design concept:

Interesting in relation to the innovation is the concept of the Dominant Design (Anderson & Tushman, 1990). This concept refers to a *technical cycle* in which, after a period of ferment, a specific design of a product becomes dominant (Figure 2). In the 'Era of ferment' many innovations take

place and contribute to the overall development of the technology. At a specific moment one of those 'designs' gains a dominant position due to its acceptance in the marketplace, technological superiority and/or economic characteristics. Whatever the case, the design has 'impact'. This (then dominant) design – being recognized as the basic innovation - is then followed by the 'Era of Incremental change'. A period with incremental innovations that improve on the dominant design step by step creating a technological trajectory. In total the technical cycle creates— stretching the cycle along the time-axis— a 'cluster of innovations' with the basic innovation (= dominant design) at its core (Figure 3). Clusters of innovations which we will define as: *"A collection of innovations within a specific technology that precedes, parallels and follows ('surrounds') a basic innovation."*

Schumpeter already noted this clustering of innovations: *"[...] because the new combinations are not, as one would expect according to general principles of probability, evenly distributed through time [...] but appear, if at all, discontinuously in groups or swarms."* (Schumpeter & Opie, 1934, p. 223). He did not specify their differences. That is done by the dominant-design concept refining the 'cluster of innovation' concept which qualifies the innovations in a technology cycle. Its gives the dominant design as 'basic' innovation a place in the cluster, identifies the innovations leading up to the dominant design, and explains the incremental innovations that were an improvement on the dominant design. In the frame 'Incandescent Lamps' the example of the technological trajectory of the incandescent lamp is given and visualized (Figure 3).



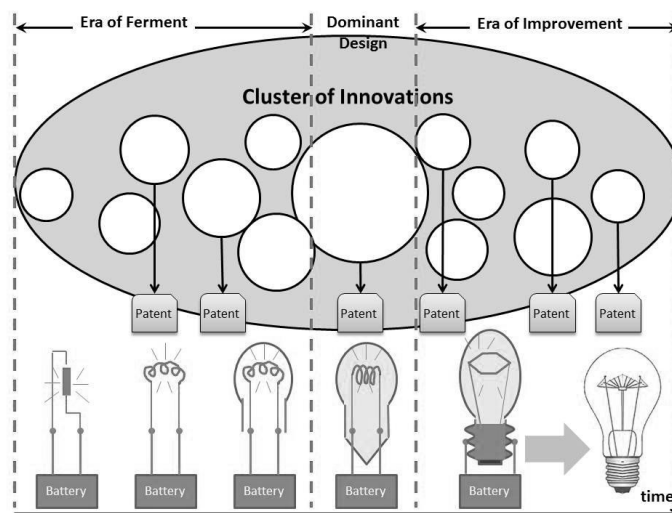
Based on: Tushman & Anderson: Technology cycles, Innovation streams ..... (1997)  
**Figure 2: Technology cycle-model and the Dominant Design-concept.**

## Incandescent lamp

The development of the electric lamp, from the early beginning of the nineteenth century leading up to the arc light, to the development of the incandescent lamp in the second half of the nineteenth century, was a stream of innovations. It started with the early efforts to experiment with Volta's wet cell. Shortcutting the cell would result in 'electric sparks' or a red hot glowing wire. The first would lead to the arc lamp, the second to the incandescent lamp.

*The technological development trajectory of the incandescent lamp:* This was a development effort to cross the 'voltaic gap' with a wire (i.e. platinum melting at 1770 °C). Certainly, it created a glow, but it would not last too long (life span: minutes). Placing the filament in an open vessel of glass did not solve the problem. To protect the filament from burning (oxidation) it was placed within a closed glass globe filled with helium. That was marginally better (life span: hour). Changing from precious metals to uncoated cotton thread and thin carbon filaments and placing it in a vacuumized closed vessel, improved the life span considerably (to a dozen hours or so). Further optimizing the design elements (better vacuum, high resistance carbonized bamboo filament) resulted in the Edison lamp: a design that would dominate the electric light for decades. Further improvement related to the coating the bulb, using tungsten for a filament, argon as a gas, standardization of the fitting. Seen in its totality, the development of the incandescent lamp was a cluster of innovations, quite a few identifiable by their patents (King, Swan, Sawyer-Man). It was Edison who created the dominant design of the incandescent lamp and patented it. But he did more, he designed the system of electricity supply (i.e. dynamos) and distribution of electricity, originating from the old gas distribution system. He created the total electric lighting system, hence wielding the impact in the marketplace and society.

More in: (Friedel & Israel, 2010; Hargadon & Douglas, 2001).



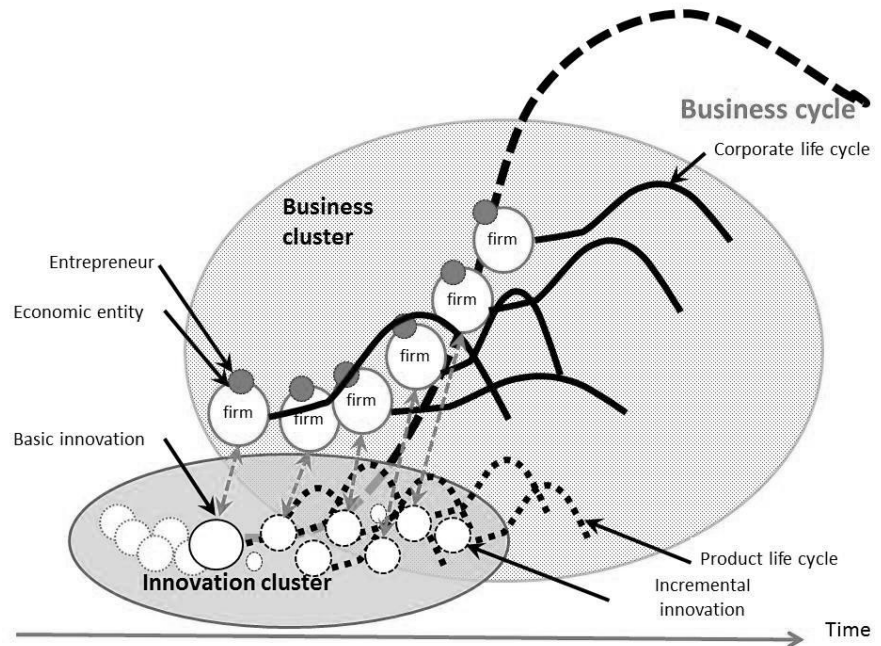
**Figure 3: Visualized technological trajectory of the incandescent lamp (schematically) related a) to the technology cycle and b) to the 'cluster of innovations'-concept.**

**Schumpeter's Business Cycle Concept:** Where all this does leads us? Well, the basic innovations (the dominant designs with their economic impact) are being exploited by entrepreneurial activity to create business. Other entrepreneurs follow creating business activities and circumventing, imitating, copying, or taking licenses of the dominant design. One could say, to paraphrase Schumpeter, a 'swarm of businesses'

would be the consequences of a 'swarm of innovations', as entrepreneurs start to economically exploit the innovation. It is the entrepreneurial activity that is linking '(product) innovation' and 'business creation'. And its aggregate is linking 'clusters of innovations'

with 'clusters of businesses' (Figure 4). The

entrepreneurial act creating new businesses (e.g. lamp-manufacturing, cable manufacturing, electric equipment manufacturing), and thus creating new industries replacing earlier industries (e.g. the electric lamp industry replacing gas lamp industry). Economic dynamics caused by innovations collected in a 'cluster of innovations' then create the business cycle with its creative destruction (Schumpeter, 1939).



**Figure 4: The Business cycle: Cluster of Businesses as the result of a Cluster of Innovations.**

**Bresnahan and Trajtenberg's GPT concept:** Innovations, basic innovations, clusters of innovations, clusters of economic cycles (business cycles, industry cycles) are related through technology. Technology with its own development trajectory and innovations streams, spawning into other, related, trajectories. It is all about technology creating 'technology cycles'. Technology (in short: "Knowing how to make things") means 'tools and techniques'. *"The concept of technology incorporates (at least) two interrelated meanings. First, technology refers to material and immaterial objects – both hardware (e.g. products, tools and machines) and software (e.g. procedures/processes and digital protocols) - that can be used to solve real-world technical problems. Second, it refers to*



*technical knowledge, either in general terms or in terms of knowledge embodied in the physical artifact.*" (Bergek, Jacobsson, Carlsson, Lindmark, & Rickne, 2008, p. 407). To be more precise, knowledge is related to techniques: *"Techniques constitute what I have called prescriptive knowledge – like any recipe they essentially comprise instructions that allow people to "produce", that is, to exploit natural phenomena and regularities in order to improve human material welfare. The fundamental unit of the set of prescriptive knowledge has the form of a list of do-loops (often of great complexity, with many if–then statements), describing the "hows" of what we call production."* (Mokyr, 2005, p. 1122). The GPT-concept tries to explain the major changes that took place in societies and economies where a dominant technology is having a major impact on society. The GPT-concept is about *meta*-technologies (e.g. steam technology, electric technology, communication technology, information technology), so at the foundations of the GPT-concept we find *technology*. And technology is both *knowledge* (the cumulated know-how) and *skills* (the cumulated learned abilities) carried, executed and implemented by people that initiate, create and facilitate innovation. The concept of the General Purpose Technology focusses on the specific characteristics of meta-technologies as 'engines of economic growth' (Bresnahan & Trajtenberg, 1995). The technological dynamism is the core of the GPT that are generally characterized by their *pervasiveness* (their pervading use over a wide range of economic and technical sectors), *technological Improvement* capabilities (the continuous improvement in its own application sector or technical trajectory) and their *technological spawning* capabilities (the creative spawning of product and process innovation in new application sectors and creating new, parallel, technological trajectories) (Jovanovic & Rousseau, 2005). These characteristics are the properties of the 'general purpose engine' themselves. Both the steam engine and the electric motor, having the product function of 'creating energetic continuous rotary motion', are examples. They were continuously improved on, and spawned into a multitude of new application areas as 'rotative power' is used for quite some general purposes (e.g. electric appliances).

### 3. Methodology framework

Given the preceding 'theoretical tour d'horizon' of the concepts used, we will now zoom in on our analysis.

**Clusters of innovation:** A conclusion that could be drawn from the preceding is the importance of the 'cluster of innovation' concept. Given the fact that there exist clusters of innovations (Figure 5), it is obvious that not all innovations in a cluster are equal. We will exploit that distinction as follows.

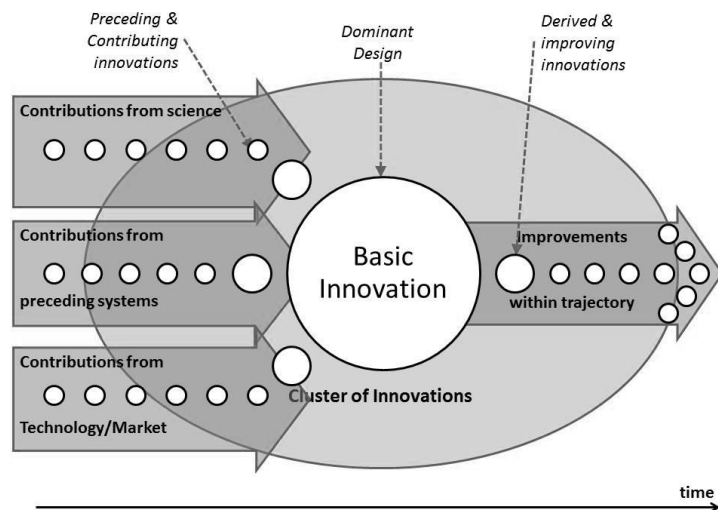


*Preceding and contributing innovations:* There is the technical development trajectory where (partial to the system) inventive activities lead to the moment when the dominant design of a basic innovation appears. This trajectory consists of the *preceding and contributing innovations* – the stepwise changes in (part of) the function of the relevant system in the Era of Ferment. These contributing innovations include the efforts by scientist and engineers to create (experimental) artifacts, the efforts of inventor/entrepreneurs who created earlier (product) innovations, and the contributions from other technological developments. Maybe the preceding innovations have not been succeeding in the market place due to technical or commercial failure, but they have been contributing to its technical development one way or the other.

*Basic innovation:* Then there is the basic innovation that is the Dominant Design that had impact (in technology, in the market, in society) and that originated the technological trajectory for further developments.

*Derived and improving innovations:* Finally there are those identifiable derived innovations that resulted *from* the basic innovation. In a technical trajectory of incremental changes in the function of the system that is improved, adapted to other environments, included into other systems (that tried to circumvent the patented solution).

Thus we define the concept for the *cluster of innovations* as a construct of 1) a *basic innovation* with 2) the *contributing innovations* and 3) the *derived innovations* (see Figure 5). As these latter are by definition different from basic innovations, the contributing and derived innovations represent smaller changes. This leads to the definition that an innovation cluster (resp. a cluster of innovations) is a *collection of interrelated innovations incrementally contributing to, and deriving from, a basic innovation.*



**Figure 5: The cluster of innovations: the basic innovation preceded by contributing innovations (left side), and followed by derived innovations (right side).**

**Types of contributions:** A further distinction can be made in those contributing innovations as they relate to activity that draws upon *formal knowledge* and *previous experience* to create *solutions for needs*.

*Science contributions:* There is formal knowledge being the result of scientific work (the upper arrow in Figure 5). “[...] *progress in general scientific knowledge yields a widening pool of potential technological paradigms.*” (Dosi, 1988, p. 1136). Work resulting in the discoveries of new and useful knowledge about products and processes as the result of ‘research’. Depending on the moment in history this ‘research’ grew from the informal inventor active in his ‘workshop/model room’, to the later in time appearing formal organized ‘research laboratories’.

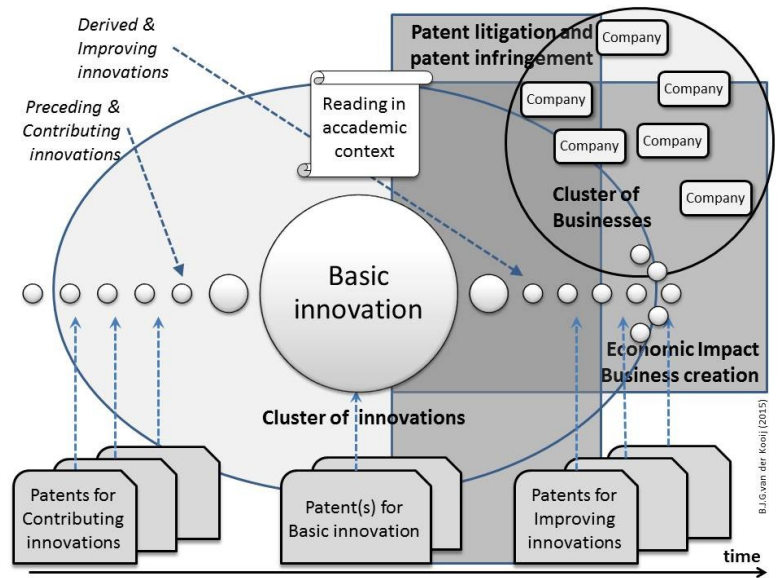
*Contributions from previous systems:* The earlier developments of artifacts and systems also contribute to the culmination of experience (the middle arrow in Figure 5). This is the *knowledge base* innovators use looking for innovative solutions: “*an important part of the knowledge base consists of tacit knowledge about the performance of previous generations of machines, their typical conditions of use, the productive requirements of the users, and so on.*” (Dosi, 1988, p. 1126).

*Technology/Market contributions:* Realizing that innovation is about finding the solution to a perceived or latent user problem (i.e. a ‘need’), it involves activity that is accumulated tacit knowledge of knowing ‘how to make things’ (that is: ‘technology’). It is technology and market that define the boundaries for innovation: “[...] *technological innovation involves the solution of problems – for example, on transformation of heat into movement, shaping materials in certain ways, producing compounds with certain properties – meeting at the same time cost and marketability requirements.*” (Dosi, 1988, p. 1125). The market thereby is representing the need (the lower arrow in Figure 5).

This leads us to the distinction of the input-dimension of the cluster model at hand: science, previous systems and technology & market. The resulting model we used for our analysis of the case studies.

**Innovation identifiers:** The last thing to do relates to the identification of the innovations. Identifying innovations is not that complicated as we have already a tool for that: the patent system. Realizing that using patents as indicators has its specific considerations (Kleinknecht, Van Montfort, & Brouwer, 2002), and that not all innovations are patented, it is a given fact that all patents are – by definition – related to innovations: “*The grant is issued to the inventor of this device or process after an examination that focuses on both the novelty of the claimed item and its potential utility.*” (Griliches,

1998, p. 288). As we only want to identify the *existence* of the innovation, the patent is usable for the *presence* of an innovation, as an ‘innovation indicator’. This use of patents as indicator is often illustrated, for example for the innovations in steam technology (Sullivan, 1990, p. 355), (Nuvolari & Tartari, 2011, p. 16) and electric technology (Moser & Nicholas, 2004). When needed we complemented the identification by other indicators (like the readings at the Royal Society of London) (Figure 6).



**Figure 6: The innovation identifiers: patents for innovations; the basic innovation identified by patents, conflicts and economic impact/business creation.**

When qualifying innovations in order to identify the basic innovation, more is needed than just identification by patents. Here we have to look at the (economic/technical) impact of the innovation. Economic impact resulting in business creation, fierce competition between companies, shake-out, mergers and acquisitions within industries. And technical impact in terms of product performance, cost performance, influencing further technical developments and external spillovers. Both impacts in a dynamic situation that, among other factors, often can be indicated by the patent litigation/infringement — that sometimes are escalating in ‘patent wars’ — related to the specific innovation. When those patent litigations were not identifiable in the ‘fog of history’, we looked at the literature and depended on the judgments of others. As we were not interested in the complicated ‘who is the first to invent’-discussions, this seemed appropriate to do.

#### 4. Case studies

Based on the theoretical framework we created the operational model for our interpretation, and applied it in the following case-studies: the case studies of the *Invention of the steam engine*, the *Invention of the electromotive engine*, and the *Invention of the electric light*. Let’s have a look at the real developments as they happened to be.

## 4.1 The invention of the steam engine

The Invention of the steam engine has been investigated quite extensively — and especially the readers of the Transactions of the Newcomen Society should be familiar with it. Using our perspective the well-known creative endeavors of Savary, Newcomen, Watt and Threvithick resulted in a development trajectory that took more than a century. In this stream of innovations certain clusters of innovations with distinct basic innovations can be distinguished. The totality of these basic innovations had, next to some patent litigation, an enormous impact on society. It contributed to the First Industrial Revolution because it touched on a basic issue: the replacement of human, animal and natural power. Taking the patents identified by Nuvolari et al. (see Table 1 ) as a starting point we identified three clusters of innovations: one cluster around the Newcomen engine, one cluster around the Watt engine and one cluster around the Trevithick engine.

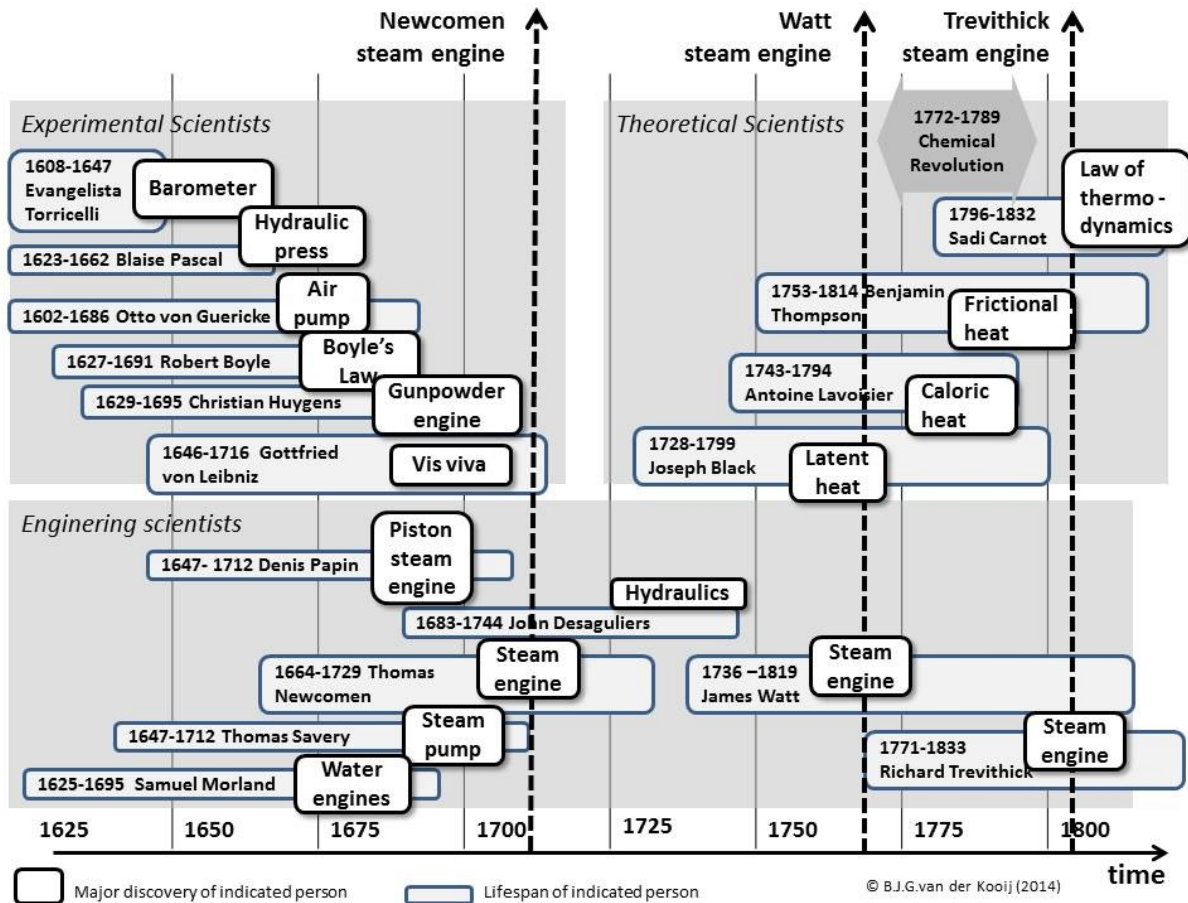
**Table 1: Basic patents in the development of the GPT Steam**

Patent #	Year	Patentee	Invention
GB №. 356	1698	Thomas Savery	Steam engine (Newcomen)
GB №. 913	1769	James Watt	Steam engine (Watt condenser)
GB №. 1063	1774	John Wilkinson	Boring Machine
GB №. 1351	1783	Henry Cort	Iron Making
GB №. 2599	1802	Andrew Vivian	High pressure steam engine (Trevithick)

Source: (Nuvolari & Tartari, 2011) Derived from Table VII.

The development of the steam engine has to be seen in the contexts of their time: eighteenth century England and Europe. Not only socially a dynamic period (with its own madness of times), economically flourishing (mercantilism, colonialism), but also the scientific context was relevant (Figure 7). After the discoveries made by the *Experimental Scientists* (Torricelli, Pascal, von Guernicke, Boyle, Huygens, von Leibnitz), gradually more insight was obtained in the phenomena of hydraulics, air pressure and steam. Theories created by the *Theoretical Scientists* ranged from the ‘Phlogiston theory’, still based on the four elements water, fire, earth and air, to the ‘fluid theories’ (Black, Lavoisier, et al). Then came the early *engineering scientists* that experimented with the artifacts (Papin, Savery, Morland). Their work was either related to the splendor of nobility (i.e. Moorland), or attracted military and industrial interest (Savery, Papin). After all, the water problem in mines had to be solved, and military would (at first reluctantly) use other means of ship propulsion by wind power.

In Figure 8 the ‘cluster of innovations’ for each of the three steam engines are shown along the time-line. It clearly shows that Watt ‘s steam engine is one of several engines that in total constitute the creation of the steam engine. It is a range of three basic innovations in which also the basic innovations

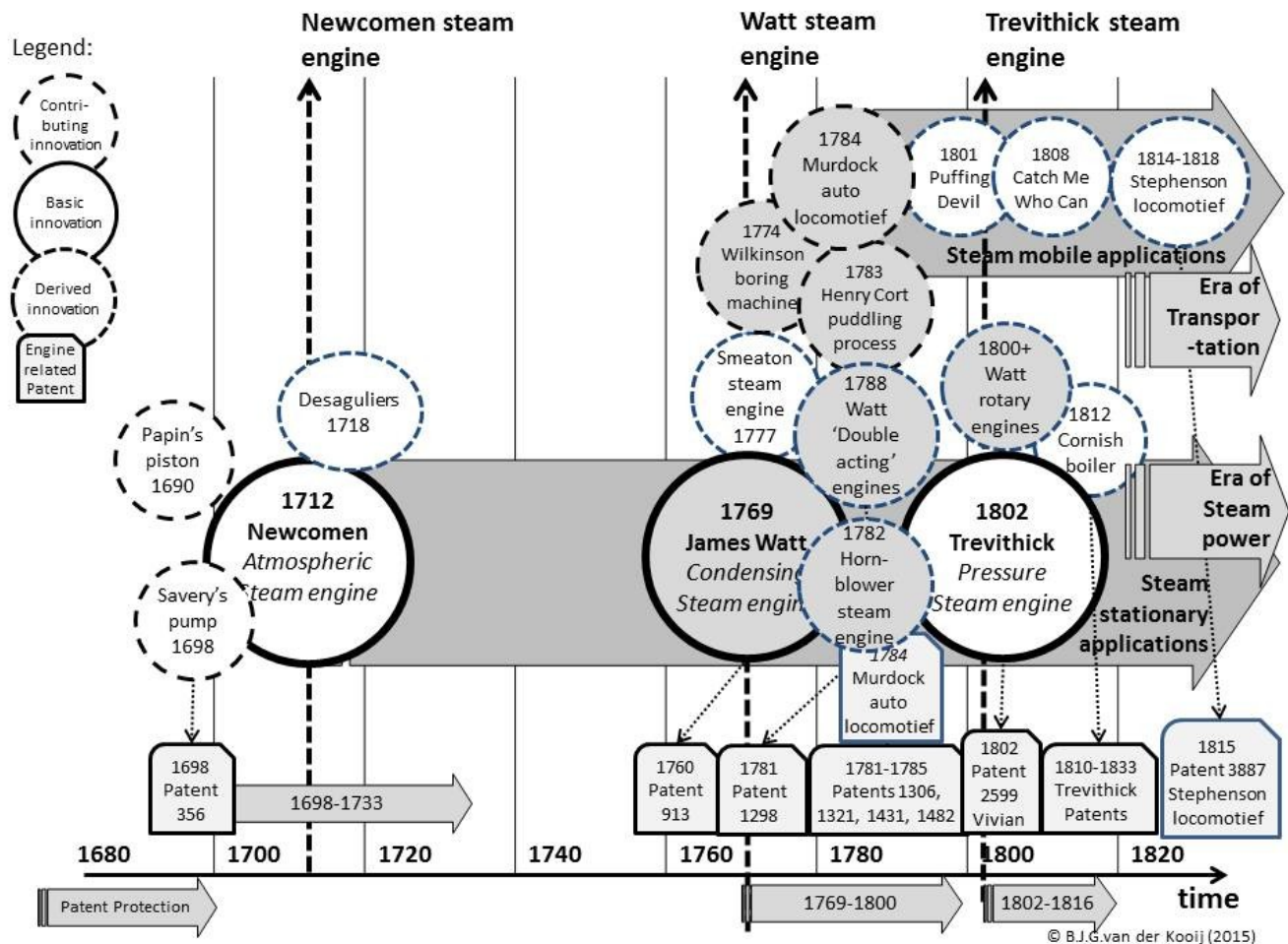


**Figure 7: Science discovers steam: the scientific context.**

of Newcomen and Trevithick had also a considerable impact on the development. The patent-period indicator shows (bottom of figure) shows the period of protection for the specific basic innovations. For some scholars it was the long-active Watt 1769-patent that inhibited progress. Till Trevithick could develop his engine after the patent expired.

As the multi-purpose 'steam technology' is - in retrospect - considered to be contributing considerably to the Industrial Revolution, it is considered to be a General Purpose Technology: "... in the second half of the nineteenth century steam power penetrated every aspect of economic life in the Western World and beyond." (Mokyr, 1990, p. 92) Especially the developments around Watt's and Trevithick's engines show considerable clustering. The ongoing development of the steam engine from atmospheric to condensor-based engine and high-pressure engine, indicate its potency for improvement, the introduction of the steam engine – next to stationary applications - in mobile applications indicates its spawning potency (B.J.G. van der Kooij, 2015c).





**Figure 8: Overview of innovation clusters with their basic innovations that resulted in the 'general purpose' steam engine.**

Source: B.J.G. van der Kooij. *The Invention of the Steam Engine* (2015) p. 110

## 4.2 The invention of the electromotive engine

Next we went on to the case study on the GPT-Electricity. 'Electricity' being a too broad description, we narrowed it down to 'electro-motive engines' (B.J.G. van der Kooij, 2015b). The case-study started as 'the invention of the electro-motive engines': the electromotor and the electric dynamo. But it became much more than that when we observed the innovations of the early electric lights (B.J.G. van der Kooij, 2015).

In the following we will describe the 'invention' (in its broad meaning, from discovery to innovation) of the electromotive engine. Again, it is not one invention, but a massive collection of innovations. Contrary to the historic folklore of the steam engine, the development of the electro-motive engine does

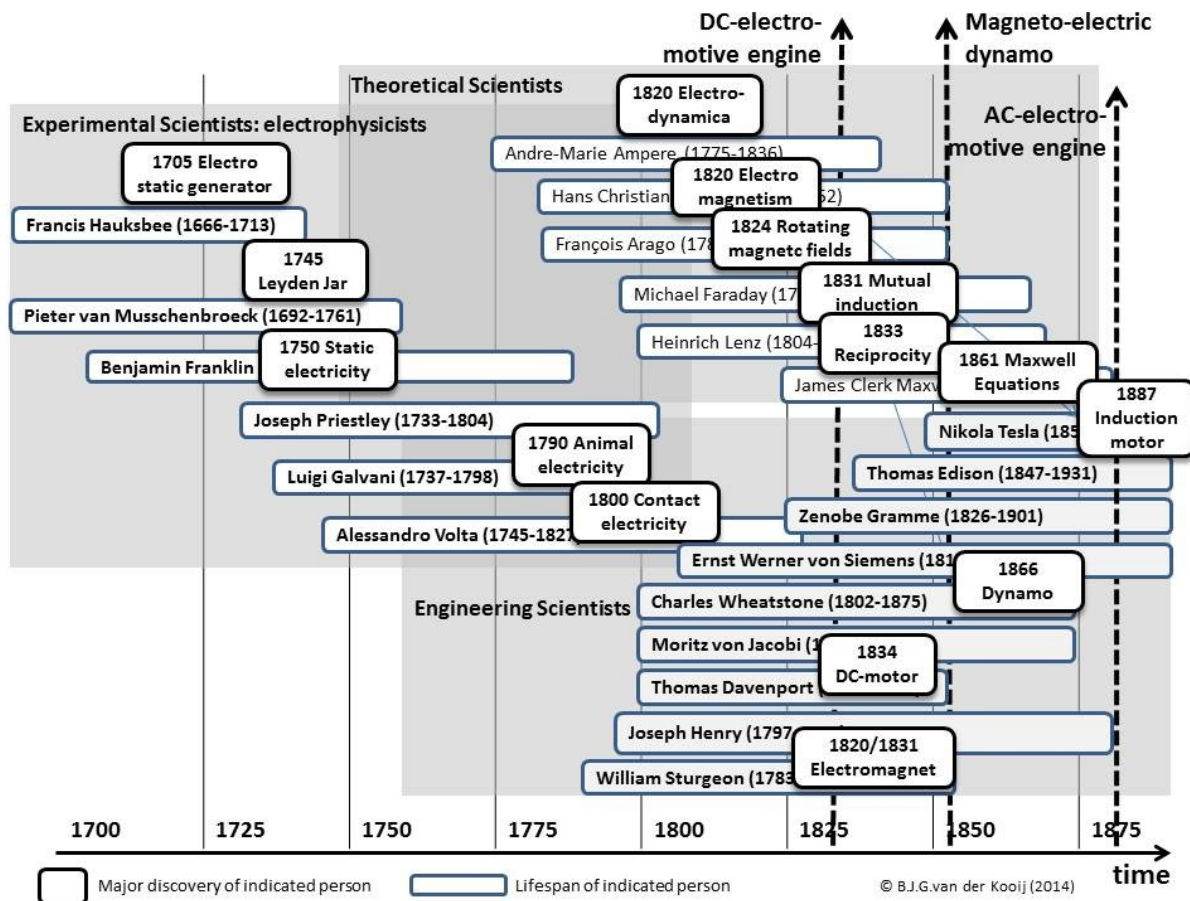
not mention too many heroes. It is more in the application of electricity that heroes like Thomas Edison (electric lamp), Samuel Morse (electric telegraph) and Alexander Graham Bell (electric telephone) appear. As far as patents are concerned, in Table 2 are shown the patents we identified as being relevant to three clusters of innovations: around the DC-motor, the electric dynamo and the AC-motor.

**Table 2: Basic patents in the development of the GPT Electricity**

Patent #	Year	Patentee	Invention
<b>US No. 132</b>	1837	Davenport	DC-motor
<b>US No. 295.454</b>	1888	Sprague	DC-motor (railway applications)
<b>US No. 494.978</b>	1892	Crocker/Wheeler	DC-motor (machine applications)
<b>GB No. 806</b>	1855	S.Hjorth	Dynamo-Electric generator
<b>GB No. 3.394</b>	1886	S.A. Varley	Dynamo-Electric Generator
<b>GB No. 261</b>	1867	W.Siemens	Dynamo-Electric Generator
<b>US No. 292.079</b>	1884	Jonas Wenström	Dynamo-Electric machine
<b>US No. 381.968</b>	1888	Nicola Tesla	Two-phase induction motor
<b>US No. 390.439</b>	1888	Charles Bradley	Two-phase induction motor
<b>US No. 427.978</b>	1890	M. Dobrovolsky	Three-phase induction motor
<b>Fr No. 112.024</b>	1876	Pavel Jablochhoff	Electric-Arc light
<b>US No. 223.898</b>	1880	Th. Edison	Incandescent Lamp

To place the developments in context we analyzed the contributions of early scientists who studied the phenomenon of the ‘nature of lightning’ (see Figure 9). It were the early *electro physicists* like Hauksbee, van Musschenbroeck, Franklin, Priestly and Galvani that studied the phenomenon of electricity. They observed static electricity, animal electricity and chemical electricity. The discovery of Volta’s wet cell as a source of electric energy spurred a massive interest among the more *theoretic scientists*. Among those Hans Oersted who discovered the electro-magnetism, Andre-Marie Ampere who formulated electro-dynamism and Michael Faraday who discovered electro-motive rotation and mutual magnetic induction. It was the spreading of the know-how about Volta’s cell and Hans Christian Oersted’s electromagnetic experiments that stimulated many scientists all over Europe. Not only scientists, but also *engineers* like the American blacksmith Thomas Davenport and the German engineer Moritz von Jacobi. Together the experimental engineers and theoretical scientists created the foundations for the development we analyzed to be appearing in clusters of innovations:

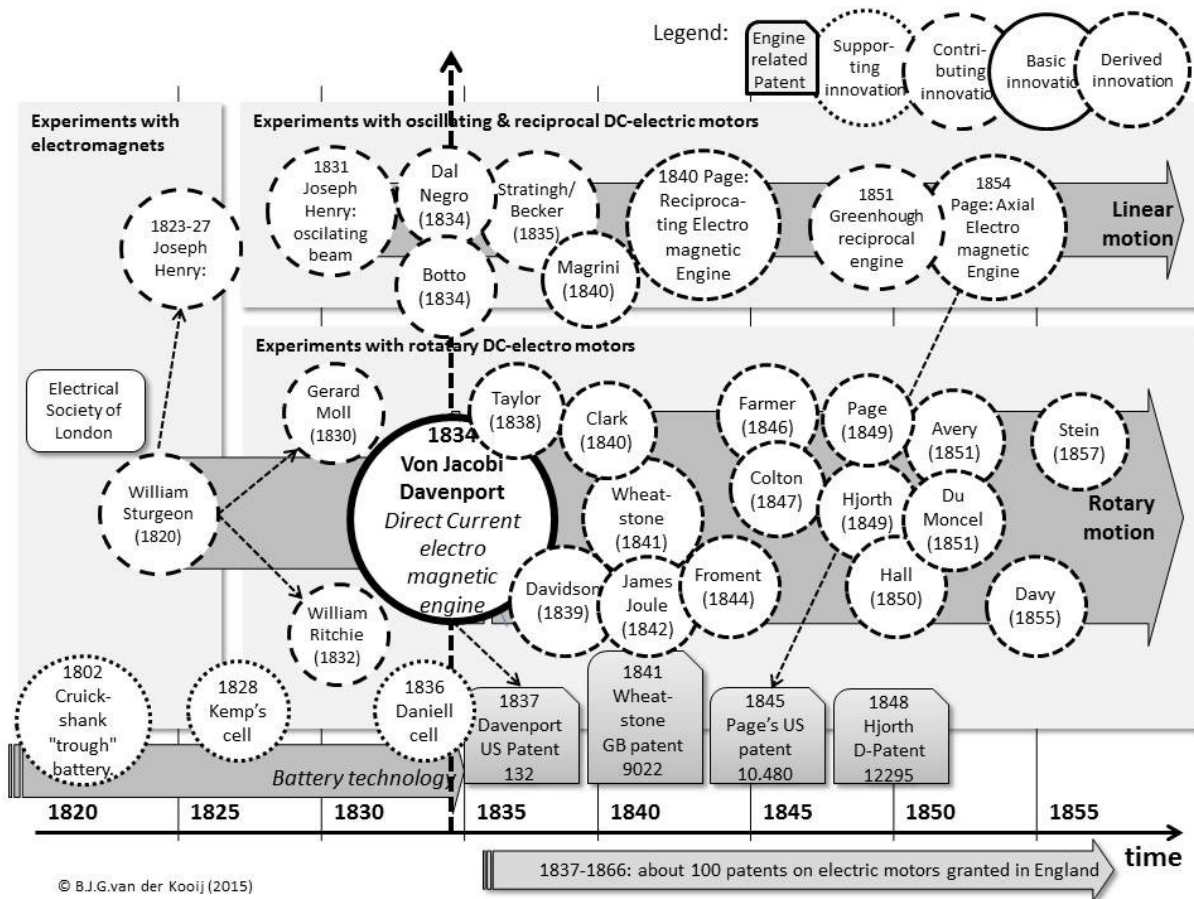




**Figure 9: Science discovers electricity: the scientific context.**

Source: B.J.G. van der Kooij. *The Invention of the Electro-motive Engine* (2015) p. 70

*First cluster: the DC-electric engine* (Figure 10). The DC electro-motive engine was the direct result of the experimenting of the 'engineers scientist' creating electromagnets (Surgeon, Henry and others). Others, copying the reciprocal movement of the steam engine, developed linear electromagnetic motors. It proved to be a 'dead end technology'. But those who created rotary movement in the form of the first rotary electromotive engines (Von Jacobi, Davenport) proved that electricity was able to create rotative motion. In Europe it was Von Jacobi who constructed, financed by the Russian Czar, an electrical powered boat paddling on the river Newa in St.Petersburg. He reported in 1835 on it at the Paris Academy of Sciences. In London it was Davenport who demonstrated in 1837 his small electric train and obtained one of the early US-Patents (No. 132). They were followed by a multitude of inventors creating Direct Current (DC)-powered electromotive engines (Stimson, Hjorth, and others). But these early forms of the electromotor did not become successful as they were powered by those awkward batteries. Although improvements created better 'wet cells' (Cruikshank, Kemp, Daniell



**Figure 10: Cluster of innovations around Davenport's and von Jacobi's electromotive engine.**

Source: B.J.G. van der Kooij. *The Invention of the Electro-motive Engine* (2015) p. 86

and others) over time, their electric power supply was limited; they often had to be replaced, refilled and renewed. The lack of an adequate supply of electric power seemed an impregnable barrier.

*Second cluster: the dynamo (Fout! Verwijzingsbron niet gevonden.)*. With the invention of the **magneto-electric dynamo** - also called the 'dry cell' - electrical energy became available in abundance. The electric motor is based on the quality that electricity, using magnetism, can create rotary movement. In addition, there exists the reciprocal situation, in which rotary movement, using magnetism, can create electricity. This was soon discovered (Lenz and others) and a new device was born: the magneto-electric engine. Using a steam engine or waterwheel as prime mover supplying the rotative power, the engine produced electricity in two 'flavors': Alternating Current (AC) and Direct Current (DC).

Many engineering scientists experimented with this concept (Jedik, Pixii, and others) creating machines that could produce electricity in abundance. But always using a steam engine, or waterwheel, as primary source of energy. Many 'electricians' (Woolrich, Holmes, Wilde, and others) created their own versions of the new source of electricity, each having its own limitations. The Englishman Holmes tried, not too successful, to power the arc light in a lighthouse with a dynamo. The American Brush dominated in a curse and a sigh the arc-lighting markets with his lighting system. However, it was the creation of the self-exciting dynamo (Varley, Wheatstone, Siemens) that created a breakthrough. In 1867 Varley patented (too late to obtain priority), Siemens published (at the Berlin Academy of Sciences) and Wheatstone demonstrated (at the Royal Society of London) similar innovations. Reliable, low cost and low maintenance electricity became available. The self-exciting engine would become the standard for electricity-generations and create the stimulus for the electric light applications. And the electric light in turn would fuel further developments of the dynamo. Soon a bonanza of manufacturers supplied dynamo's (Gramme, Brush, Edison and others). More than 50 US patents and more than 200 GB-patents would be granted for dynamo-innovations in the years

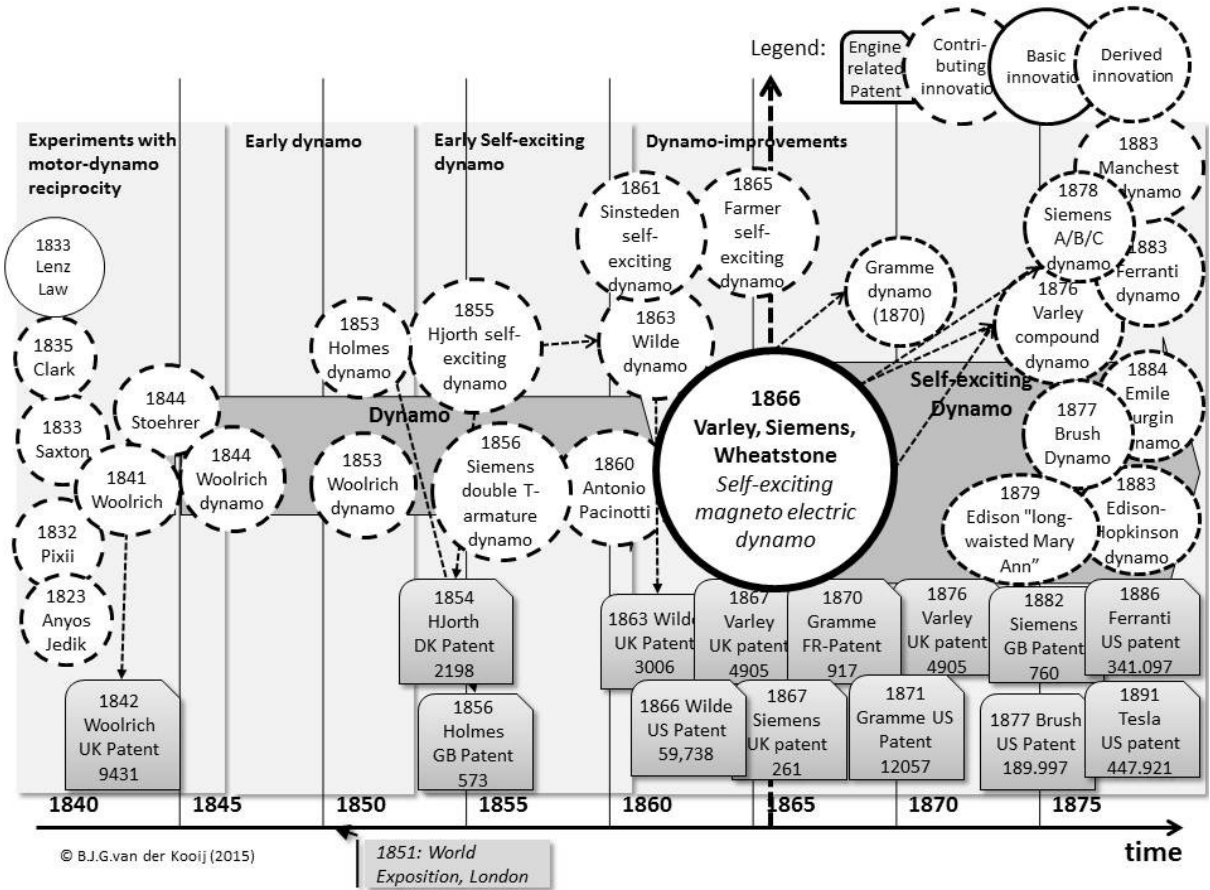


Figure 11: Cluster of innovations around Varley’s, Siemens and Wheatstone’s self-exciting dynamo.

Source: B.J.G. van der Kooij. *The Invention of the Electro-motive Engine* (2015) p. 130

after 1867.

As noted before, the electro motive engine powered by electrochemical batteries (by nature DC) was not successful. That changed when the DC-dynamos created an abundance of electricity. In the second half of the nineteenth century, when the electric lamp had fueled the development of an urban and municipal infrastructure of electricity supply (through the new and fast emerging ‘utility industry’), the DC-electromotor became popular (Figure 12, top arrow). For example: in individual transportation where the horse-powered streetcars were replaced by electrical powered streetcars (1887: Richmond Union Passenger Railway), and it was used in elevators of the high-rise construction in New York (Sprague and others). Or in machine applications where small DC-motors would power a lathe, a sewing machine, a fan and a dentist drill (Diehl, Wheeler and others). But the DC-motor had its limitations (sparking, starting torque) and was hindered by a basic DC-problem: the limited areas DC supply-networks could service. Thus DC-electricity was only powering densely populated areas (i.e. the First District in New York).

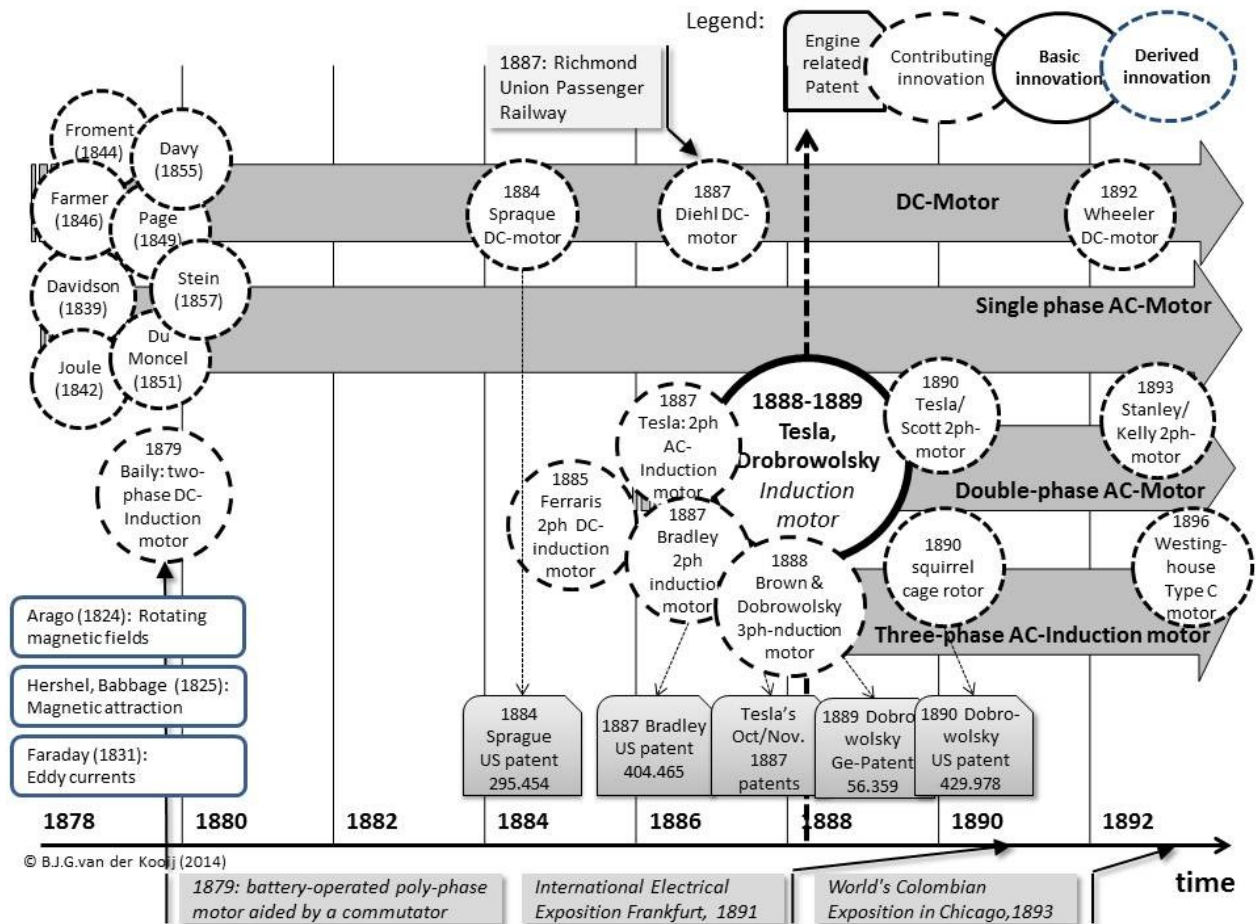


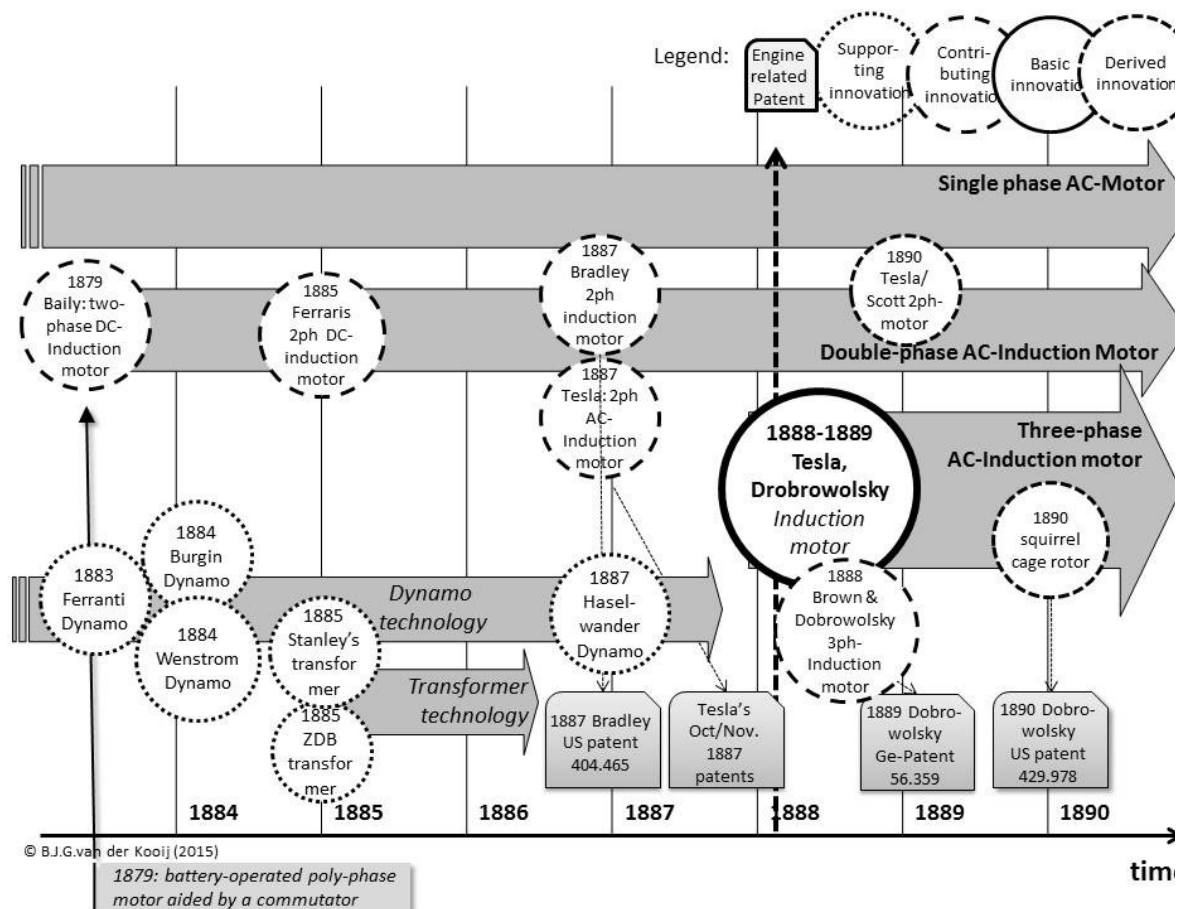
Figure 12: Developments related to type of electricity: the DC-motor (top) and the AC-motor in the single-phase, double phase and three-phase power system.

Source: B.J.G. van der Kooij. *The Invention of the Electro-motive Engine* (2015) p. 198



Two breakthroughs were needed, one of them being the development of a self-starting, simple and reliable electric motor. The other being a distribution network in which electricity could be supplied over larger areas and be generated at the source of the primary mover (e.g. the Niagara Falls). The solution to both problems was the poly-phase Alternating Current (AC) of higher voltage than DC. After scientists had understood the inner workings of AC-electricity and electromagnetic induction (Arago, Deprez, Ferraris, Faraday and others) (Figure 9), many AC-motors were developed (Figure 12, second arrow) and early high voltage AC-distribution networks were created (in the US, Germany and Sweden). This became possible through the applications of the step-up and step-down transformer (Gaulard-Gibbs, Zipernowsky and others) and the AC-network concept (Wenström and others). Then Tesla and Dobrovolsky created in 1888-1889 a completely different electromotive engine, the induction motor, using the rotating electromagnetic field created by the poly-phase AC (both 2-phase and 3-phase AC). The resulting machine was simple, robust, powerful and self-starting.

*Third cluster: the AC-motor* (Figure 13) Soon, the induction concept was used in a technological trajectory with a multitude of improvements (Bradley, and others) that were patented. It was the



**Figure 13: Cluster of innovations around Tesla's and Dobrovolsky's induction motor.**

Source: B.J.G. van der Kooij. *The Invention of the Electro-motive Engine* (2015) pp. 159-197.

three-phase AC-network concept (using three phase generators, transformers and induction motors) that victorious came out on top after the 1891-Exhibition in Frankfurt am Main (Germany). Then the single phase and three-phase AC-induction motor was soon used in an abundance of applications that needed a rotative power source. From household appliances (i.e. the washing machines, the frigidaire) to industrial applications (i.e. pump, fans blowers, tools and machines). The two-phase system did not gain momentum.

In the accompanying figures we have identified for each of the basic innovation – the DC-motor, the self-exciting dynamo and the AC-motor - the clusters of Innovations that surrounded them. In Figure 14 along the timeline an overview is shown of these basic innovations and their cluster of innovations. It shows the main trajectory with the reluctant development of the DC-motor that was hindered by its energy source (the wet cell). Then it was the self-exciting dynamo created by Siemens, Wheatstone and Varley, that created the breakthrough by making electricity available in abundance. Later the DC-motor

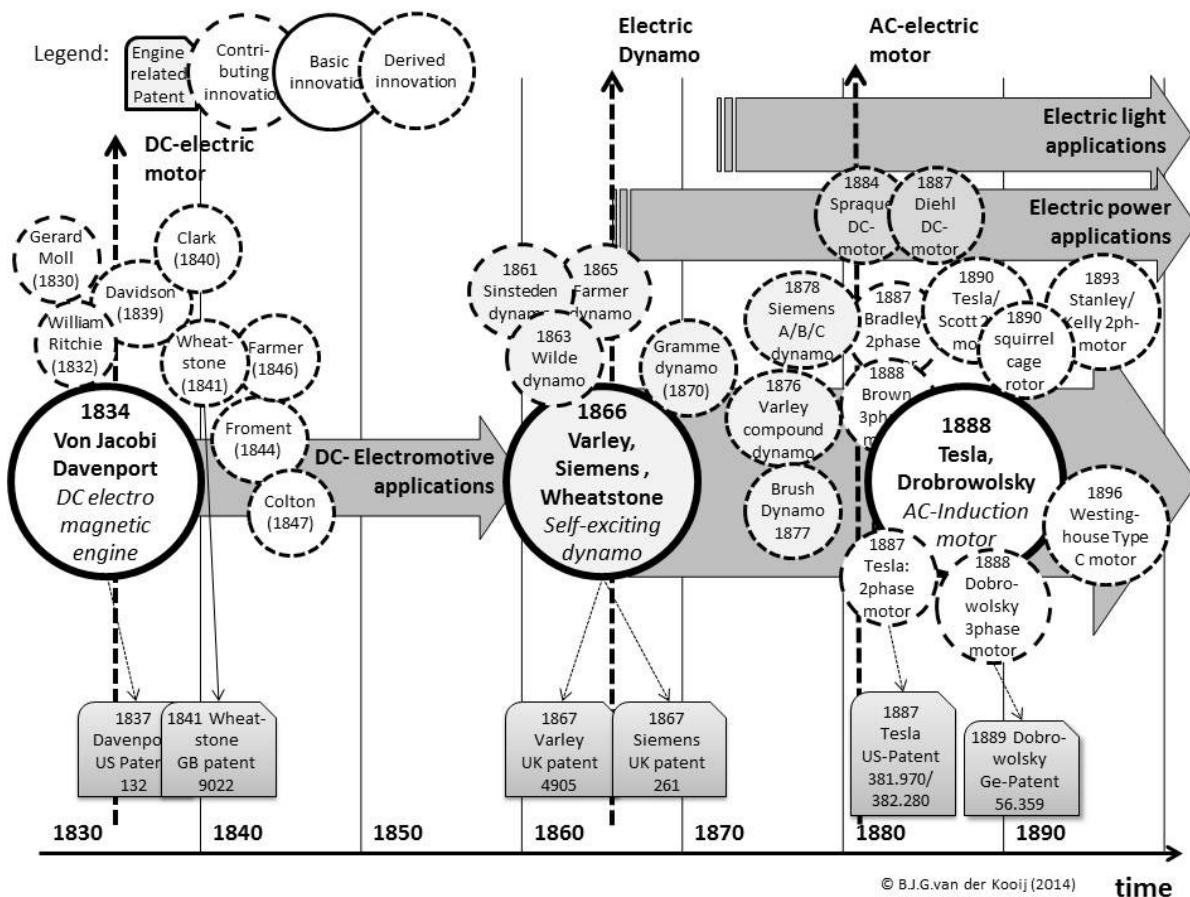


Figure 14: Overview of innovation cluster with their basic innovations that resulted in the 'general purpose' electromotive engine.

Source: B.J.G. van der Kooij. *The Invention of the Electro-motive Engine* (2015) p. 230

got a revival and was used many electric power applications. And the development of AC-distribution systems would result in an infrastructure that could support early AC-motors. When next the AC-induction motor was developed by Tesla and Dobrowolsky a wealth of applications for AC-electro motors would become available. The development shows a remarkable pattern: the relation of the dynamo and its accompanying infrastructure. In this case the distribution infrastructure for electricity.

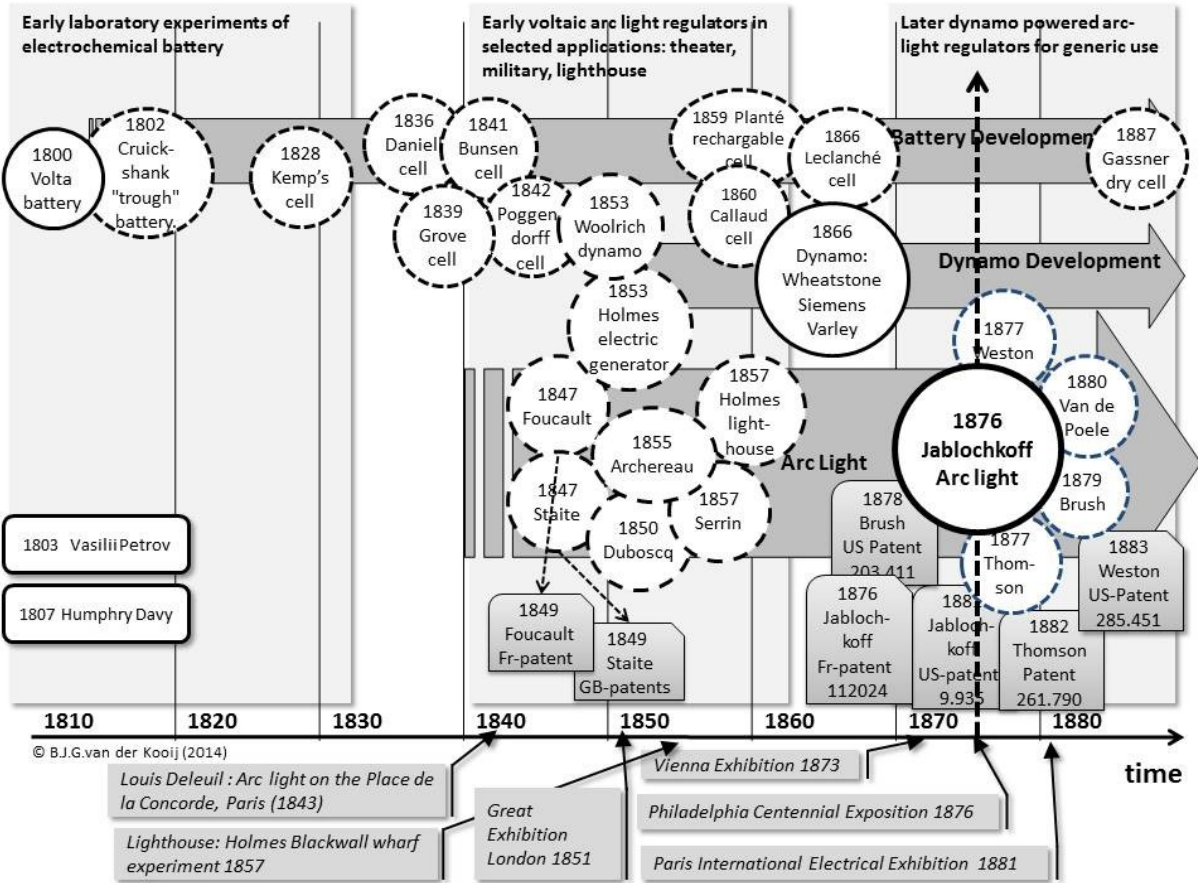
### ***4.3 The invention of electric light***

The abundance of electricity resulted in several developments. As illustrated, one of them being the development of the DC-motor that was picked up again (Sprague, Crocker, and others). It changed public transportation from horse-powered carriage to electric trams. It made high-rise buildings more accessible with electric powered elevators. DC-motors were used to power appliances (ventilation fans, washing machine, etc.) and machines (lathes, etc.). This would become known as the Era of Power. But an even larger new field of application was found in electric lighting: first the electric arc light, soon to be followed by the incandescent lamp.

*Fist cluster: the arc light* (Figure 15). The early experiments of Vaslii Petrov and Humphry Davy creating the arc-light with large battery systems, created a bright light between two carbon rods crossing the 'voltaic gap'. As the two rods were positioned *in line* — their points facing each other — and they would be close enough together, the arc would start and emit a bright white light. The carbon rods being too far away from each other, the arc would extinguish. During its (short) lifetime it rapidly consumed the carbon rods, increasing the gap. So it was important to control the distance. The early artifacts created to control that distance between the carbon rods were mechanical, later to be followed by complicated electro-mechanical, regulators (Statie, Serrin and others). They were implemented in showcases (i.e. exhibitions, street lighting, department stores) flabbergasting the public. But their life-time was short (hours), they smelled foul and their light was not 'comfortable to the eye'. Next to that they needed maintenance (the batteries discharged quickly, carbons had to be replaced) and their use was limited to specific applications (public places like streets, stations). Improvement in battery technology (Grove, Daniell and others) helped only marginally.

Two factors changed that situation; one was in the regulation of the carbons to maintain a correct gap, the other was in the electric power supply. First it was the Russian Pavel Jablochkoff, living in Paris, who placed the carbon *parallel* to each other so that the spark could be maintained longer without a





**Figure 15: Cluster of innovations around Jablochhoff’s electric arc light.**

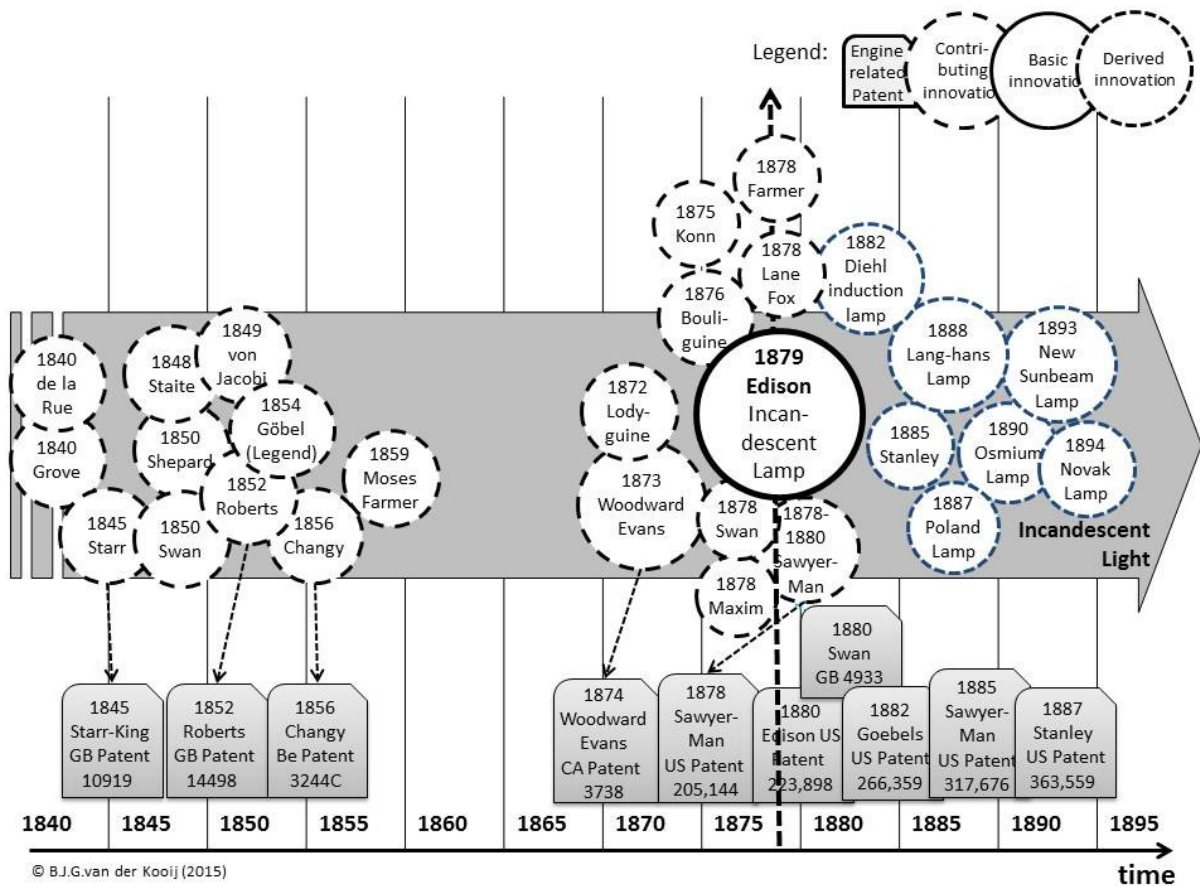
Source: B.J.G. van der Kooij. *The Invention of the Electric Light* (2015) p. 82

complex regulatory mechanism. Thus lengthening the lifetime and reducing the need for (much and costly) maintenance.

The other factor was the availability of the new developed magneto-electric generator as power source: the self-exciting ‘dynamo’ developed by Siemens, Gramme, and others. Now an abundance of electricity became available (**Fout! Verwijzingsbron niet gevonden.**). A bonanza of manufacturers, established by inventor-entrepreneurs, soon offered arc light systems (Brush, Weston, Houston Thompson, Ferranti and others). Arc light penetrated society, not only with street lights, but soon into restaurants, factories, theaters. But - because their nature in which they were to be placed in serial circuits – arc lights still were unable to penetrate in the home- and office environment as they could hardly be switched on individually and at will.

*Second Cluster: the incandescent light* (Figure 16). Another effort to cross the ‘voltaic gap’ was by bridging it with a filament (basically a thin wire of precious metal). Just like burning wood glowing in the fireplace it gave a comfortable light. In the mid-nineteenth century scientists and experimenters (DelaRue, Groove, Farmer, and others) created the first artifacts. They were short-lived as the filament burned quickly in the air. As the dynamo made electricity easily available, the filament-concept was followed by many in their development efforts (Starr, Woodward, Sawyer, Swan and others). Developments that took place in the US and in Europe (i.e. England, France, Germany). They replaced the precious metal by carbonized materials, made a closed glass container for the filament, and tried inserting specific gases and creating vacuum to lengthen the lifespan (some hours) of the filament. But their early incandescent lamps still were not practical. In the meantime the development of the vacuum-technology continued (Sprenger and others). It would be an important contribution to the realization of the incandescent lamp.

Then it was Thomas Edison, inventor by profession and dedication, who created a breakthrough when he developed a high-resistance filament out of carbonized bamboo in a vacuumized glass



**Figure 16: Cluster of innovations around Edison’s incandescent lamp.**

Source: B.J.G. van der Kooij. *The Invention of the Electric Light* (2015) pp. 100-144

bulb. In combination with his DC-generators he created and demonstrated complete lighting systems in densely populated areas (Pearl Street in New York; Holborn Viaduct in London, 1881-Exhibition in Paris). In houses, offices, hotels his electric lamps could be switched on individually, replacing the former gas lights and giving a safe light that was “comfortable to the eye”. After he patented his incandescent lamp, many others imitated and copied his concept, even invented around his patent by modifying it slightly (Sawyer, Stanley and others); thereby causing a patent war because Edison chose to defend his intellectual rights (Figure 17). The Edison incandescent lamp would dominate the market in the following decennium.

As said before, the self-exciting AC dynamo created the breakthrough for the development of electric light. All those early developments that were hindered by the limitations of the wet cell, now gave place to an abundance of new developments in electric light in the 1870s. Both the arc light and the incandescent light, using the dynamo as a power supply, followed their own development trajectory. But due to its versatility, light quality and economics, the incandescent lamp became dominant in the market and many inventor-entrepreneurs were creating businesses to manufacture them. It created an industry

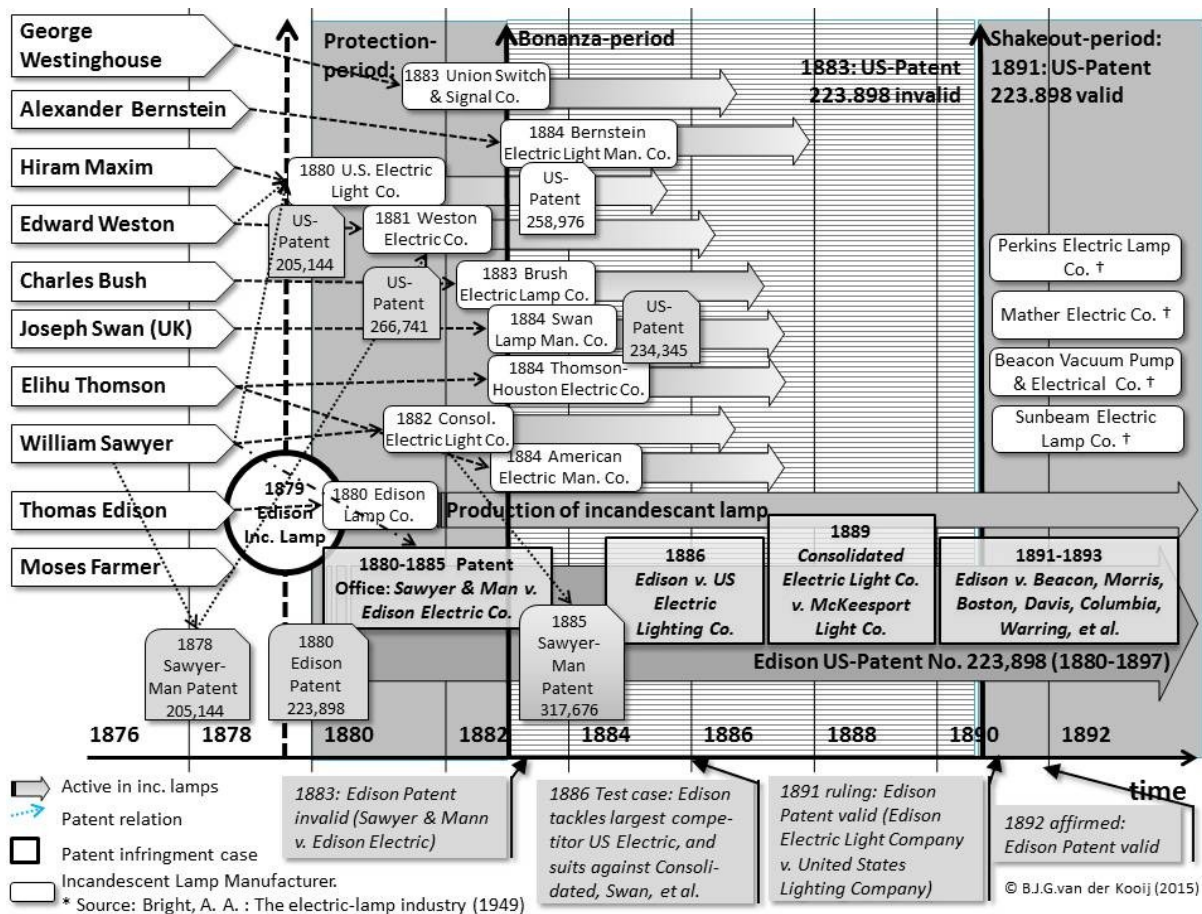


Figure 17: Patent litigation and patent wars around Edison’s patent № 223,898.

Source: B.J.G. van der Kooij. *The Invention of the Electric Light* (2015) p. 150

with its own dynamics: from patent war (Figure 17) to massive mergers and acquisitions (Figure 18).

The new industry of the electric lamp manufacturers was the result. The inventor-entrepreneurs (Hiram Maxim, Elihu Thomson, Charles Brush and numerous others) started their own business and created thus the 1880s bonanza. Other entrepreneurs (eg Westinghouse) entered the business. They manufactured electric lighting systems, both the components like lamps and generators, as well as the whole electric system. Edison's lamp-design was broadly copied, his patent application contested by the Sawyer & Man patent owner. In 1883 Edison's '898'-patent was declared invalid (Sawyer & Man vs Edison Electric). It took till 1891, after many infringement cases, before the patent was validated again (Figure 17). Then Edison attacked the companies copying his lamp, winning the cases. In this 'shake-out' period many companies ceased production of incandescent lamps (eg Perkins), others tried a not-infringing concept (eg Westinghouse), developed lamps avoiding Edison's patent or went out of business. The fierce competition between the companies within the 'electric industry', fought out in patent wars, next resulted in a decennium that was characterized by Mergers & Acquisitions (Figure 18). The pioneers of the '80s struggled, were attacked by Edison Electric Lamp Co. for infringement, went out of the lamp

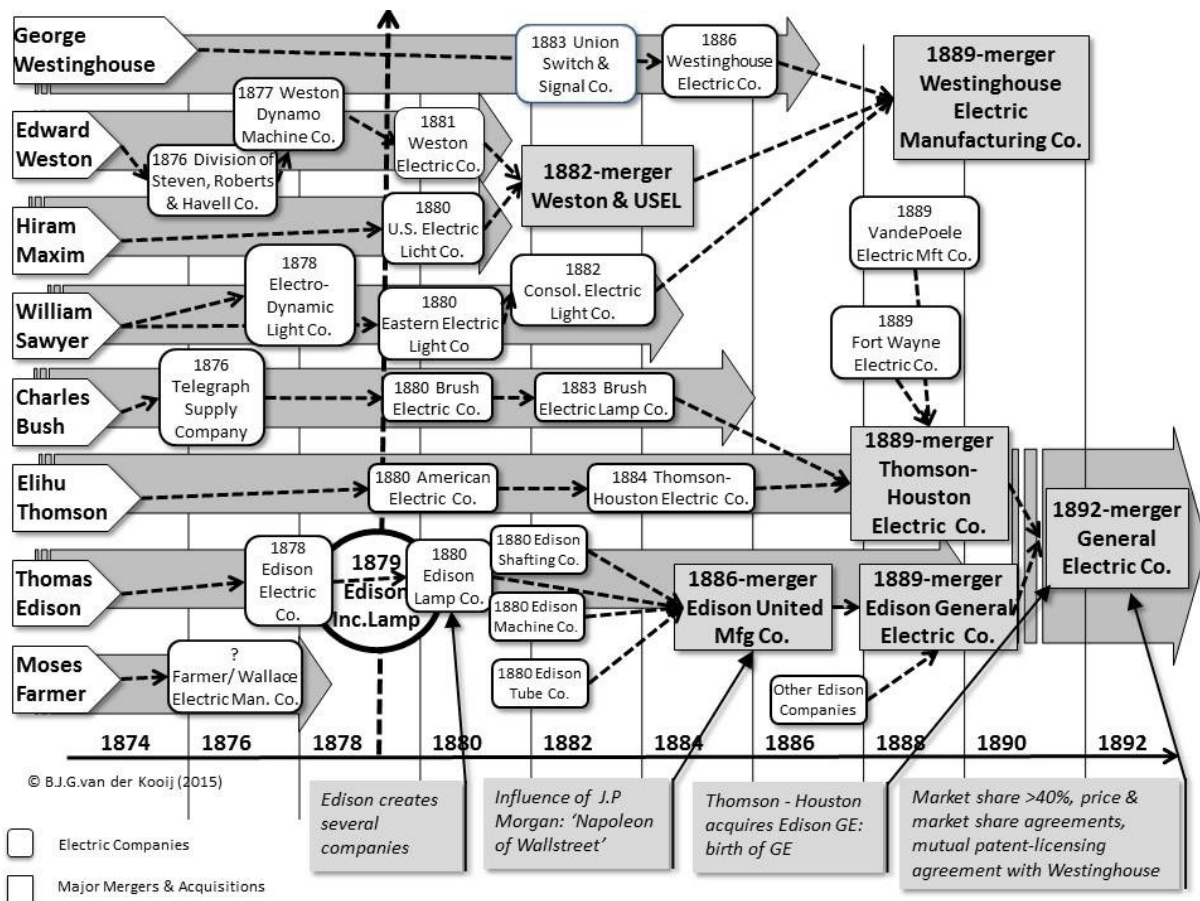


Figure 18: Mergers and acquisitions in the electric manufacturing business.

Source: B.J.G. van der Kooij. *The Invention of the Electric Light* (2015) p. 196



business or merged with other companies.

Another effect was the acquisition of smaller companies by the bigger manufacturers. George Westinghouse, an entrepreneur who got rich on his patents for automatic train brakes, decided the electric business was attractive and created Westinghouse Electric. Elihu Thompson became with the Thompson Electric Co. another dominant player in the market, acquiring many of the early pioneers (eg Brush, VandePoele). The different Edison-companies were merged into Edison United Manufacturing Co. Soon to be pressed into another merger by the Napoleon of Wall Street, the banker J.P.Morgan. Finally eg Thompson-Houston acquired Edison's General Electric Co. leading to the dominance of the US-markets by General Electric and Westinghouse Electric in the 1890s (Figure 18). By then most of 1880 startups were absorbed, and most of the inventors not any more involved in the business they created.

The development of both the arc-light and the incandescent light (Figure 19) illustrates the mutual influence of the *availability* of electricity (resulting from the basic innovation of the magnet-electric dynamo) and the *consumption* of electricity (resulting from the basic inventions of the arc-light and the incandescent light). When the wet cell ceased to be the sole source of electricity, and electric dynamo's

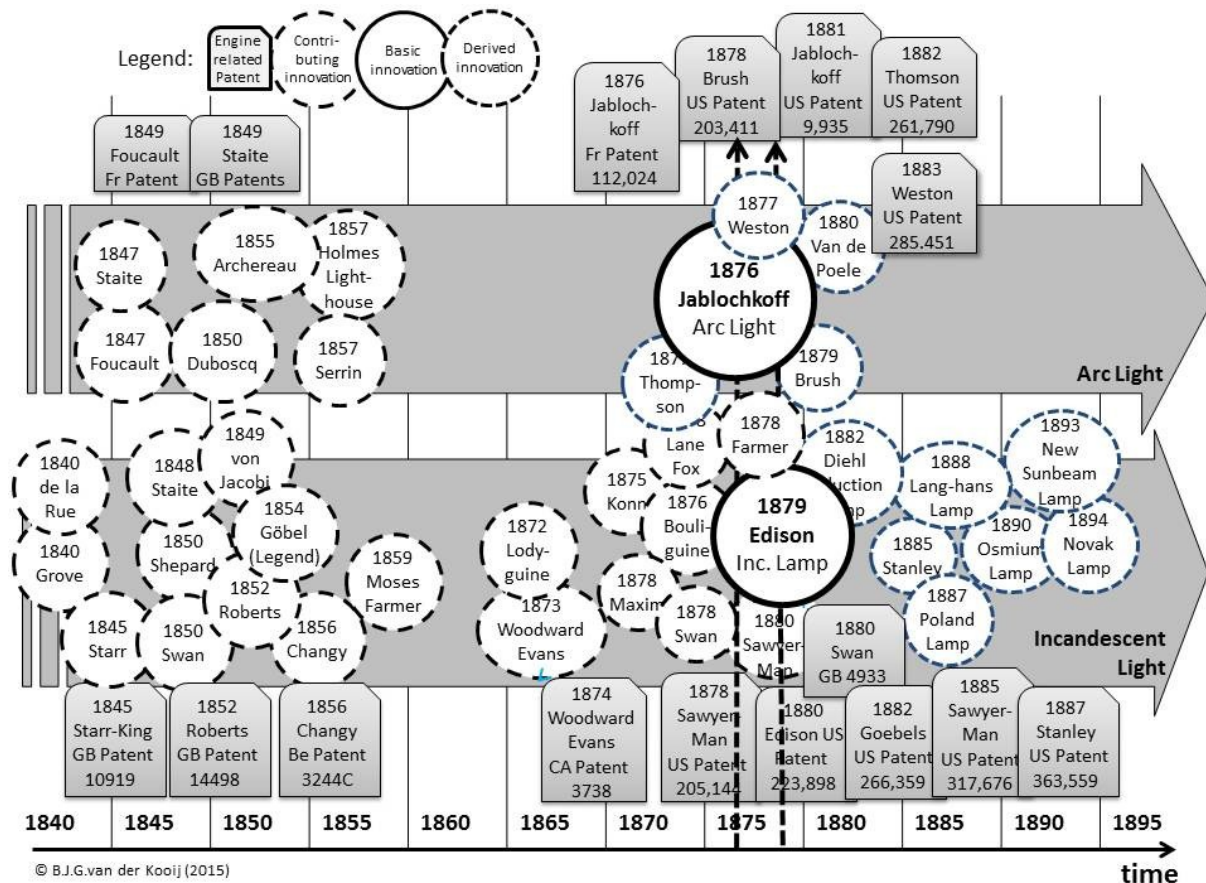


Figure 19: Overview of the Cluster of innovations of the arc light and the incandescent lamps.

Source: B.J.G. van der Kooij. *The Invention of the Electric Light* (2015) p. 202

supplied an abundance of electricity in the late 1860s, the new technology exploded into new applications. Among which was the electric light.

## 5. Conclusion

Our research identified five clusters of innovations related to ‘electricity’. Firstly the three clusters of the DC-motor, the Dynamo and the AC-motor related to the electro-motive engines (Figure 14). The cluster of DC-motor being expanded over quite some time, the cluster of the AC polyphase induction motor being quite compact. This due to the fact that the battery was replaced in the 1860s by the dynamo (Figure 12). Each of these developments followed its own technical trajectory with incremental improvements. Next, the innovation clusters of the arc lamp (Figure 15) and the incandescent lamp (Figure 16) were the result of electricity spawning into other application areas than rotative motion, namely lighting—a basic need in society. Each of the clusters showed a basic innovation having a major impact on society. Not only in terms of creating businesses with its own problems—like patent wars (Figure 17)— and dynamics (Figure 18), but also due to its influence in daily life (home lighting, home appliances) and professional life (eg office and factory lighting, powering tools and machines). Together it were the power application and the light application of the GPT-Electricity that would contribute to the Second Industrial Revolution (Figure 20).

The preceding analysis shows the different *clusters of innovations* that constitute their own General Purpose Technologies: The GPT-Steam and the GPT-Electricity (Figure 20). Based on our observations we conclude the following:

For the GPT-Steam (see Figure 8) it were the three clusters around the basic innovations of Newcomen’s, Watt’s and Threvithick’s steam engines for stationary applications, that were technically improved over time creating the *Era of Steam power* that contributed to industrialization. Then Threvithick’s engine spawned into a range of other applications. Such as in mobile applications (e.g. steam carriage, steam locomotive and steamboat, not described) creating the *Era of Transportation*. It took nearly the whole eighteenth century for the GPT-Steam to develop. The patenting of the innovations had its commercial and technical effects and certainly influenced – as can be seen in Newcomen’s and Watt’s case - the developments. It all contributed to the First Industrial Revolution (Figure 20).

For the GPT-Electricity (see Figure 14) it were the three clusters around basic innovations of the ‘general purpose engines’: like the DC-electromotive engine, the electric dynamo and the AC-electromotive engine. Each in its turn technically improved over time and was spawning into other

applications areas. Originating in stationary applications it soon moved into mobile applications (electric tram, electric locomotive, not described) and doing so created the *Era of Electric Power*. Part of the success of ‘electricity’ was created when electricity spawned into new application areas with the development of the electric lamps (see Figure 19). Their clusters of innovations created their own momentum within the *Era of Electric Light*.

This range of successive cluster of innovations, creating the *Era of Electric Power* and the *Era of Electric Light*, (Figure 20) is part of the way the GPT-Electricity — with its power-processing capabilities — contributed to the Second Industrial Revolution. The other part would relate to its information processing capabilities: the telegraph and telephone. The visitors of the Great Exhibition of London (1851) displaying the marvels of electricity, were—without realizing it— then looking at the dawn of the Communication Revolution. But that is another story.... (B.J.G. van der Kooij, 2015a)

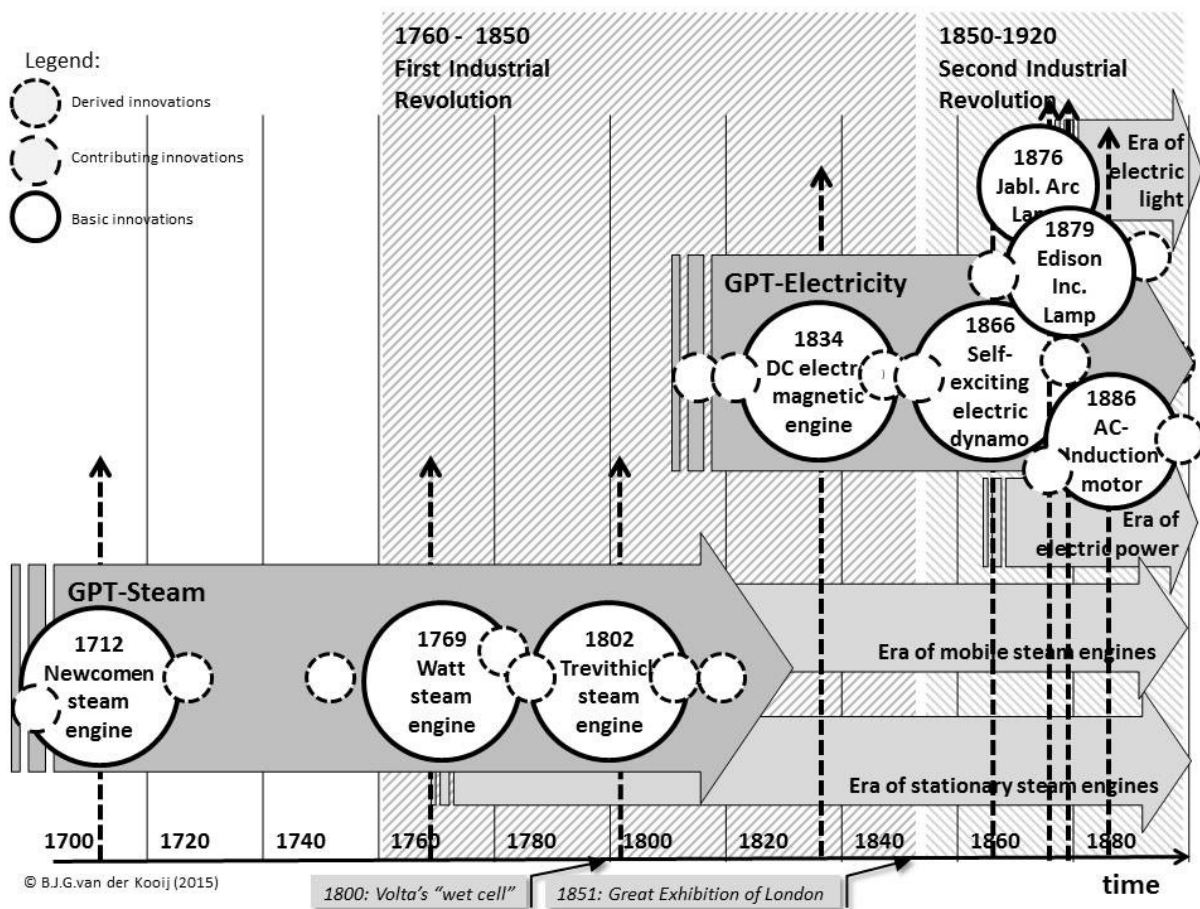


Figure 20: Overview of clusters of innovations with their basic innovations of ‘general purpose engines’ that resulted in the GPT-Steam and the GPT-Electricity.



## References

- Anderson, P., & Tushman, M. L. (1990). Technological Discontinuities and Dominant Designs: A Cyclical Model of Technological Change. *Administrative Science Quarterly*, 35(4), 604-633. doi: 10.2307/2393511
- Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., & Rickne, A. (2008). Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. *Research Policy*, 37(3), 407-429. doi: <http://dx.doi.org/10.1016/j.respol.2007.12.003>
- Bresnahan, T. F., & Trajtenberg, M. (1995). General purpose technologies 'Engines of growth'? *Journal of econometrics*, 65(1), 83-108.
- David, P. A. (1975). *Technical choice innovation and economic growth: essays on American and British experience in the nineteenth century*: Cambridge University Press.
- David, P. A., & Wright, G. (1999). General Purpose Technologies and Surges in Productivity: Historical Reflections on the Future of the ICT Revolution.
- Dosi, G. (1988). Sources, Procedures, and Microeconomic Effects of Innovation. *Journal of Economic Literature*, 26(3), 1120-1171. doi: 10.2307/2726526
- Freeman, C. (1985). The Economics of Innovation. *Iee Proceedings-a-Science Measurement and Technology*, 132(4), 213-221.
- Friedel, R., & Israel, P. B. (2010). *Edison's Electric Light: The Art of Invention*: JHU Press.
- Gilfillan, S. C. (1935). *The Sociology of Invention. An essay in the social causes of technic invention and some of its social results; especially as demonstrated in the history of the ship*. Chicago: Follett Publishing Company
- Griliches, Z. (1957). Hybrid Corn: An Exploration in the Economics of Technological Change. *Econometrica*, 25(4), 501-522. doi: 10.2307/1905380
- Griliches, Z. (1998). Patent statistics as economic indicators: a survey *R&D and productivity: the econometric evidence* (pp. 287-343): University of Chicago Press.
- Hargadon, A. B., & Douglas, Y. (2001). When Innovations Meet Institutions: Edison and the Design of the Electric Light. *Administrative Science Quarterly*, 46(3), 476-501. doi: 10.2307/3094872
- Helpman, E. (1998). *General purpose technologies and economic growth*: MIT Press.
- Jovanovic, B., & Rousseau, P. L. (2005). General Purpose Technologies. In A. Philippe & N. D. Steven (Eds.), *Handbook of economic growth* (Vol. Volume 1, Part B, pp. 1181-1224): Elsevier.
- Kleinknecht, A., Van Montfort, K., & Brouwer, E. (2002). The non-trivial choice between innovation indicators. *Economics of Innovation and new technology*, 11(2), 109-121.
- Kooij, B. J. G. v. d. (1988). Innovatie gedefinieerd; een analyse en een voorstel. Repository: University of Technology, Eindhoven.
- Kooij, B. J. G. v. d. (2013a). Innovation Defined, a Survey. Repository: University of Technology, Delft.
- Kooij, B. J. G. v. d. (2013b). Innovation Defined, a Survey.
- Kooij, B. J. G. v. d. (2015). *The Invention of Electric Light* (Vol. 4): CreaSpace, Amazon.
- Kooij, B. J. G. v. d. (2015a). *The Invention of the Communication Engine 'Telegraph'* (Vol. 3): CreaSpace, Amazon.
- Kooij, B. J. G. v. d. (2015b). *The Invention of the Electro-motive Engine* (Vol. 2): CreaSpace, Amazon.
- Kooij, B. J. G. v. d. (2015c). *The Invention of the Steam Engine* (Vol. 1): CreaSpace, Amazon.
- Lipsey, R. G., Carlaw, K. I., & Bekar, C. T. (2005). *Economic Transformations: General Purpose Technologies and Long-Term Economic Growth*: Oxford University Press.
- Maclaurin, W. R. (1953). The Sequence from Invention to Innovation and its Relation to Economic Growth. *The Quarterly Journal of Economics*, 67(1), 97-111. doi: 10.2307/1884150
- Mokyr, J. (1990). *The lever of riches: Technological creativity and economic progress*: Oxford University Press.

- Mokyr, J. (2005). Long-term economic growth and the history of technology. *Handbook of economic growth*, 1, 1113-1180.
- Moser, P., & Nicholas, T. (2004). Was Electricity a General Purpose Technology? Evidence from Historical Patent Citations. *The American Economic Review*, 94(2), 388-394. doi: 10.2307/3592916
- Nuvolari, A., & Tartari, V. (2011). *The quality of English patents, 1617-1841: A Reappraisal using multiple indicators*. Paper presented at the Paper presented at the DIME Final conference.
- Ruttan, V. W. (2000). Technology, growth, and development: an induced innovation perspective. *OUP Catalogue*.
- Scherer, F. M. (1965). Invention and Innovation in the Watt-Boulton Steam-Engine Venture. *Technology and Culture*, 6(2), 165-187. doi: 10.2307/3101072
- Schmookler, J. (1966). *Invention and economic growth*. Cambridge: [s.n.].
- Schumpeter, J. A. (1935). The Analysis of Economic Change. *The review of Economics and Statistics*, 17(4), 2-10. doi: 10.2307/1927845
- Schumpeter, J. A. (1939). *Business cycles; a theoretical, historical, and statistical analysis of the capitalist process (Fels)* (1st ed.). New York, London,: McGraw-Hill Book Company, inc.
- Schumpeter, J. A., & Opie, R. (1934). *The theory of economic development; an inquiry into profits, capital, credit, interest, and the business cycle*. Cambridge, Mass.,: Harvard University Press.
- Sullivan, R. J. (1990). The revolution of ideas: widespread patenting and invention during the English industrial revolution. *Journal of Economic History*, 50(2), 349-362.
- Usher, A. P. (1929). *A history of mechanical inventions*. New York: McGraw-Hill Book Company.
- Usher, A. P. (1955). Technical change and capital formation *In: Capital formation and economic growth* the(pp. 521-548): Princeton University Press.